

ST. ANTHONY FALLS LABORATORY

Project Report No. 584

BROWN'S CREEK THERMAL STUDY FINAL REPORT

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Executive Summary

The report summarizes an effort to construct a detailed stream temperature model for Brown's Creek, to use the model to characterize the drivers of water temperature in Brown's Creek, and to explore several temperature mitigation scenarios. A stream temperature model was assembled based on the CEQUAL-W2 package for the main stem of Brown's Creek, from the water outlet to Manning Avenue. The model water used to simulate water temperature in Brown's Creek at an hourly time step, for continuous periods (April-October) in 2012 and 2014. Surface runoff inputs were specified based on outputs from the BCWD XP-SWMM model. Baseflow input rates and temperature were specified based on monitoring data, and riparian shading conditions were specified based on tree canopy coverage estimated from LiDAR data. The SAFL MINUHET package was used to simulate the temperature of runoff inputs. Overall, the stream temperature model was able to reproduce observed temperatures in Brown's Creek with an accuracy of about 1.0 to 1.3 Celsius.

Scenario analysis using the calibrated temperature model included augmentation of riparian shading, disconnect of select detention pond inputs, and baseflow augmentation. Augmentation of shading in reaches that currently have high sun exposure was predicted to reduce stream temperatures on the order of 0.5 to 1 °C. Disconnect of Oak Glen stormwater ponds was not found to give significant reductions, however, the potential benefit of pond disconnects may be masked by low riparian shading in this reach. Baseflow augmentation in a section of Brown's Creek near the diversion structure was also found to give relatively minor changes in stream temperature, but some uncertainty exists as to the seasonal temperature of these baseflow inputs.

Acknowledgements

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I. Project Background

The stream temperature modeling effort described in this report was initiated in support of the Brown's Creek TDMDL implementation plan. Stream temperature models, along with monitoring data, provide a means both to better understand the causes of temperature impairments in streams and to prioritize various options for temperature mitigation, such as riparian shading restoration and stormwater BMPs.

This project included the assembly and testing of a dynamic stream temperature model for Brown's Creek, the collection of ancillary data for model calibration, and temperature mitigation scenario analysis using the calibrated model.

Funding for this project was provided by the Board of Water and Soil Resources and the Brown's Creek Watershed District.

II. Stream Temperature Model Assembly

The stream temperature model was assembled based on the United States Army Corps of Engineers (USACE) model, CEQUAL-W2. This 2-dimensional (2-D) model for flow, temperature and nutrient transport can be applied to lakes, rivers, and reservoirs. For modeling a well-mixed stream, the 2-D capability of the model (model over streamwise distance and depth) is not needed, but this feature may be useful in the future for modeling in-stream ponds due to beaver dams. The CEQUAL package models flow and temperature with high resolution in time, e.g. hourly time steps. An alternative stream temperature modeling package developed at the United States Geological Service (USGS), SNTMP, was considered for this project, however, SNTMP is limited to daily time steps, and therefore is not well suited for modeling the propagation of heated stormwater pulses through a small stream.

Many versions of the stream temperature model for Brown's Creek were assembled and tested. Problems were encountered in obtaining a converged solution for the stream flow, particularly at flows less than 1 cfs. Model features found to improve the convergence properties of the CEQUAL model included the following:

- 1) Short model segments improved the convergence of the flow solution— the 7.3 km long modeled reach was divided into a series of 183 elements with a uniform length of 40 m.
- 2) A single vertical layer, rather than multiple layers. Using a single layer implies that temperature is constant (well-mixed) over depth, a reasonable assumption in Brown's Creek, except in deep pools formed by beaver dams.
- 3) Modeling changes in stream slope as a change in roughness. For each major section of the model, an equivalent roughness (n^*) was calculated as follows:

$$n^* = \frac{\sqrt{S^*}}{\sqrt{S}} n$$

where n is the actual value of Manning's n , S is the actual slope, and S^* the value of constant slope ($=0.05$) used for all of the modeled stream segments. This modeling strategy reduced model

convergence problems at transition regions from low slope to high slope (e.g. downstream of the Old Stone Bridge).

The stream temperature model was broken up into 3 major sections with different rates of baseflow input and baseflow temperature (Figure 2.1). The downstream section, from the WOMP station to Stonebridge, represents a higher slope reach with relatively high rates of baseflow input with a low temperature (9 °C). The middle section, extending from Stonebridge to McKusick/Neal, represents a low slope reach with no baseflow input (based on the 2014 baseflow surveys). However, piezometer measurements in 2015 by EOR staff suggest that the middle reach was a losing reach in early summer and a gaining reach later in the year. The upper reach extends from McKusick/Neal to Manning Avenue, and is low slope with variable temperature baseflow inputs, based on the 2014 piezometer measurements. Initial versions of the model extended to 110th, but difficulties in modeling low flows, and less emphasis of this upper section in the mitigation scenarios, led to omission of this section in later versions for the model.

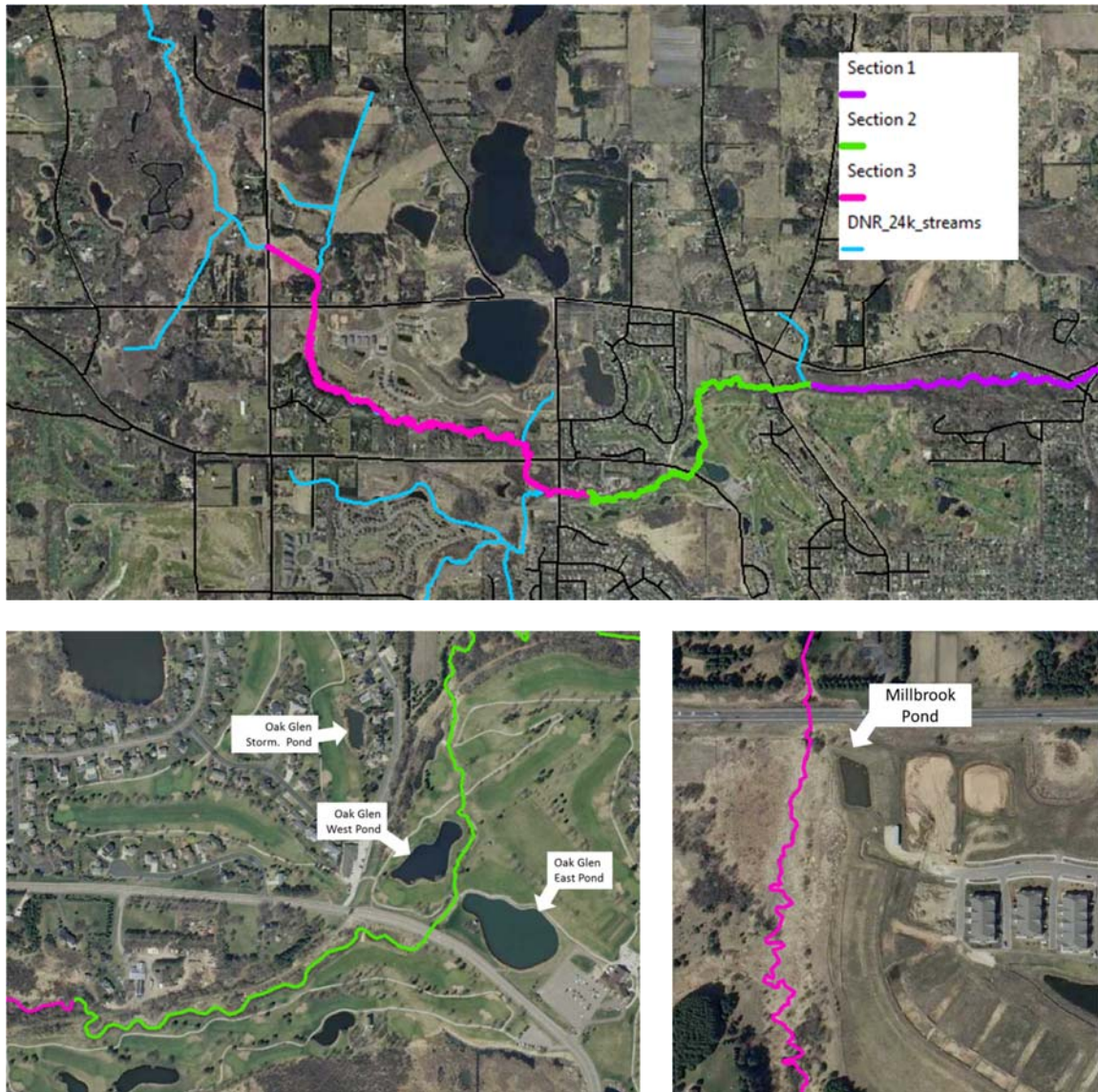


Figure 2.1. Map of the extent of the CEQUAL-W2 stream temperature model assembled in this study, from the WOMP station to Manning Avenue. The total length of the 3 model segments was 7.8 km (4.6 miles). The lower panels show details of the ponds modeled in and near the Oak Glen golf course and Millbrook pond.

The stream temperature model requires the specification of many inputs, including weather data, surface runoff inputs, and baseflow inputs from wetlands and other seepage areas. Weather data was taken from the weather monitoring station installed in the Brown's Creek watershed, including air temperature, humidity, precipitation, and solar radiation. The stream temperature model inputs for surface runoff, pond effluents, and baseflow were assembled from a combination of monitoring data and additional model components, as described below.

Baseflow Analysis and Specification

Baseflow surveys conducted in 2014 by EOR and SAFL staff were used to set the rates of distributed baseflow inputs to the stream temperature model, as shown in Figure 2.2. The baseflow measurements on 7/28/2014 and 9/30/2014 were quite consistent, except for the high value at McKusick/Oak Glen in July, which was assumed to be a bad measurement. Piezometer data taken in 2015 in this region suggests groundwater inputs may be more complex in this area than assumed based on the 2014 measurements. The fit values shown in Figure 2.2 represent the assumed relative distribution of baseflow inputs to Brown's Creek, with no inputs between McKusick/Neal and Stonebridge.

For any given moment in time to be modeled, the baseflow inputs to Brown's Creek were determined as follows. Figure 2.1 illustrates the three major stream segments in the CEQUAL model with different baseflow input characteristics.

- the total baseflow was determined from baseflow extraction of the observed flow time series at the WOMP station. Baseflow extraction techniques described in Arnold and Allen (1999) were used.
- the distribution of the baseflow inputs over the modeled stream segments was then set based on the relative distributions in Figure 2.2. 56% of the total baseflow was input to the upland segment (#3, Figure 2.1), no flow to the middle segment, and 44% to the lower segment (#1, Figure 2.1). Within each segment, the baseflow input was distributed uniformly, as suggested by Figure 2.2.

The upper stream segment (#3 in Figure 2.1) was given a simulated wetland/shallow seepage inflow temperature, as exemplified in Figure 2.5. A representative input temperature was simulated for each year simulated. The middle stream segment (#2) was assumed to have no baseflow input, based on Figure 2.2. The lower segment (#1) was given a constant temperature of 9 °C, based on the piezometer #16 temperature measurement in the gorge (Figure 2.4).

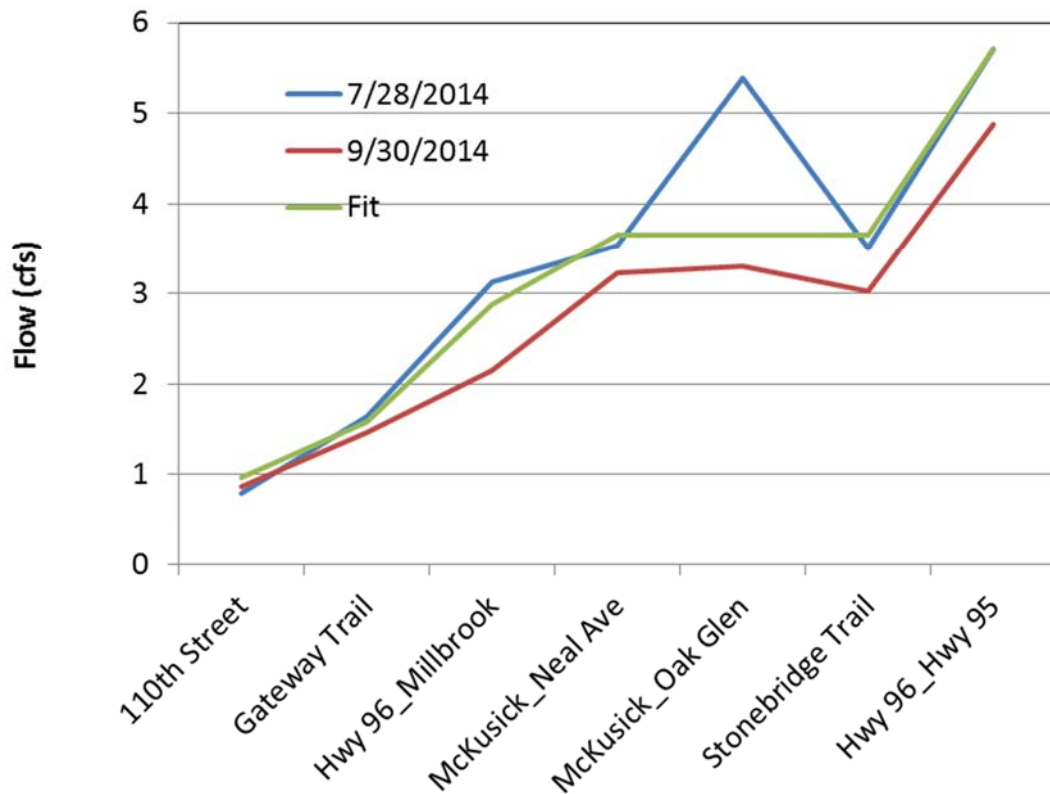


Figure 2.2. Summary of measured baseflows in Brown's Creek taken during the 2014 monitoring effort.

Baseflow and Wetland Temperature Analysis

The piezometer measurements (pressure head and temperature) taken by EOR staff in 2014 were used to calibrate the wetland temperature models. This monitoring effort included 8 piezometers in the headwaters wetland located to the north of 110th Street, and additional piezometers in groundwater seepage areas close to Brown's Creek (Figure 2.3). The head and water temperature measurements from the wetland are summarized in Figure 2.4. The down-gradient measurements (e.g. piezometers 10 and 11) show higher water level response and lower temperatures, suggesting the accumulation of shallow groundwater at the downstream end of the wetland. It was assumed that the temperatures measured at piezometers 6, 7, 10, and 11 are representative of the temperatures of baseflow supplied to the stream channel from the wetland.

Although the measured piezometer temperatures from 2014 could be used as baseflow inputs for stream temperature simulations in 2014, a wetland temperature model was used to generate representative wetland and seepage temperatures for 2014 and 2012, anticipating that these shallow subsurface flow temperatures vary from year to year. A previously developed wetland temperature model was used to simulate the annual variation of the subsurface soil/water temperature (Herb et al. 2007). The 1-D model used considers only the vertical temperature profile in standing water and the soil column, including the effects of emergent vegetation. The simulated temperature 0.5 meter below the

soil surface gave a good match to the observed wetland and seepage piezometer temperatures (Figure 2.5). These simulated daily temperatures were used to represent baseflow input temperatures in the upper reach of Brown's Creek in the two simulation years, 2012 and 2014.

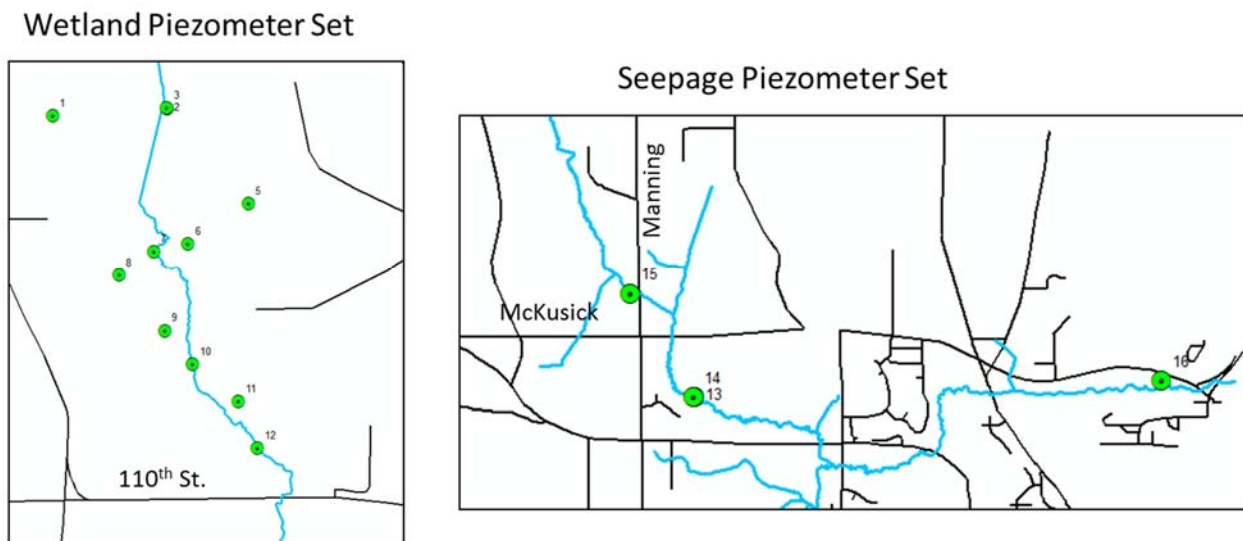


Figure 2.3. Map of the piezometer locations for the 2014 monitoring effort.

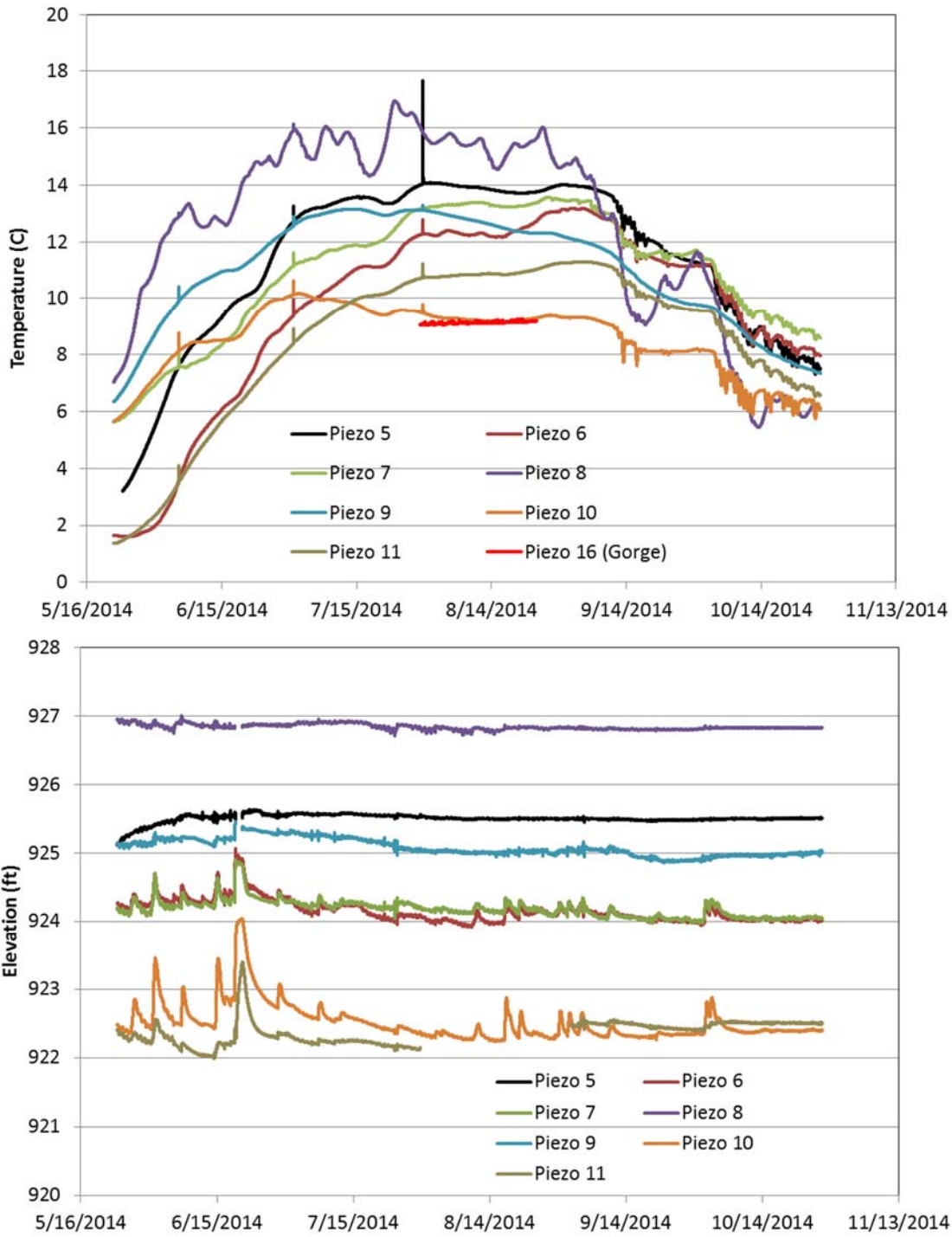


Figure 2.4. Subset of piezometer levels and temperatures from the 2014 monitoring effort. The piezometer locations are given in Figure 2.3.

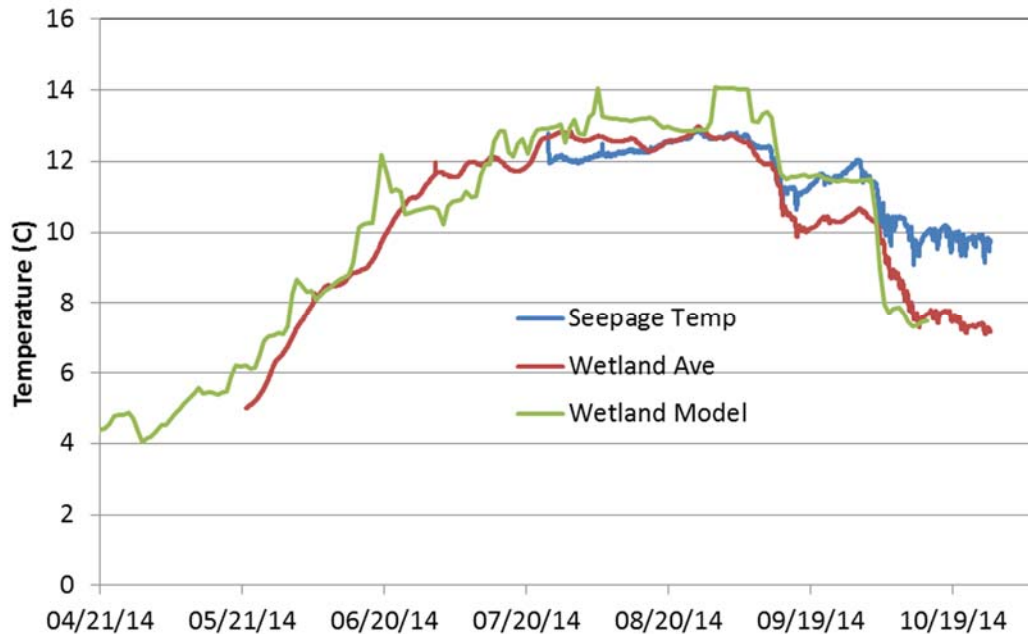


Figure 2.5. Time series of observed wetland piezometer temperatures , observed seepage temperature at Millbrook, and simulated wetland temperature. The wetland temperature plotted is the average of piezometers 6, 7, 10, and 11.

Stormwater Inflow Rates and Temperatures

Estimates of stormwater inflow rates and temperatures are important for modeling stream temperatures during and after storm events. The MINUHET package (Herb et al. 2009) was used to generate representative stormwater runoff temperatures and detention pond effluent temperatures for 2012 and 2014. Hourly runoff simulations from the BCWD's PC-SWMM model were used to establish the contributing runoff volumes for each contributing sub-catchment. Using the MINUHET and PC-SWMM simulations, hourly runoff volumes and temperatures were determined for a total of eleven direct runoff inputs. These input points were based on the non-negligible PC-SWMM surface runoff inputs to the main stem of Brown's Creek, as summarized in Appendix II. An example surface runoff rate and temperature input generated by MINUHET is given in Figure 2.6.

MINUHET was also used to generate detention pond effluent rates and temperatures for three ponds in the Brown's Creek watershed: 1) The Oak Glen East pond, 2) the Oak Glen stormwater pond, and 3) the Millbrook stormwater pond (Figure 2.1). The Oak Glen West pond was also considered, but was assumed to be discharging negligibly based on EOR staff observations. For each pond, MINUHET was used to generate a time series of pond inflows (similar to data shown in Figure 2.6) based on the estimated contributing area. MINUHET was then used to simulate a time series of the water volume and temperature profile in each pond, along with the pond discharge, as exemplified in Figure 2.7 for the Oak Glen stormwater pond. For the Oak Glen East pond, a constant groundwater seepage input was also specified in 2014 (0.03 cfs), based on baseflow survey measurements, to simulate baseflow discharge from the pond. No groundwater seepage input was specified in 2012, based on observations of EOR field staff.

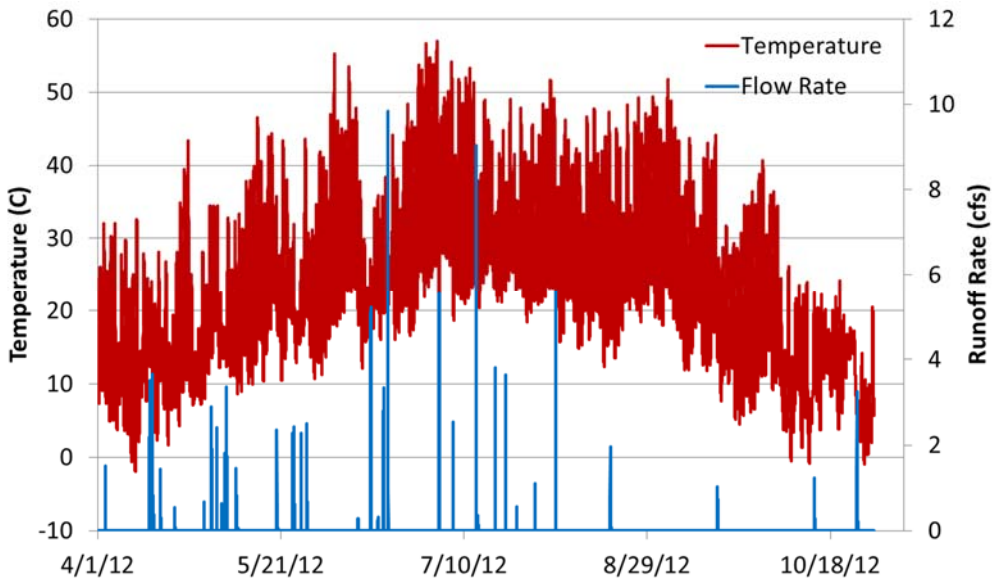


Figure 2.6. Simulated 15 minute time series of surface runoff input rate and temperatures for 2012, from the MINUHET model.

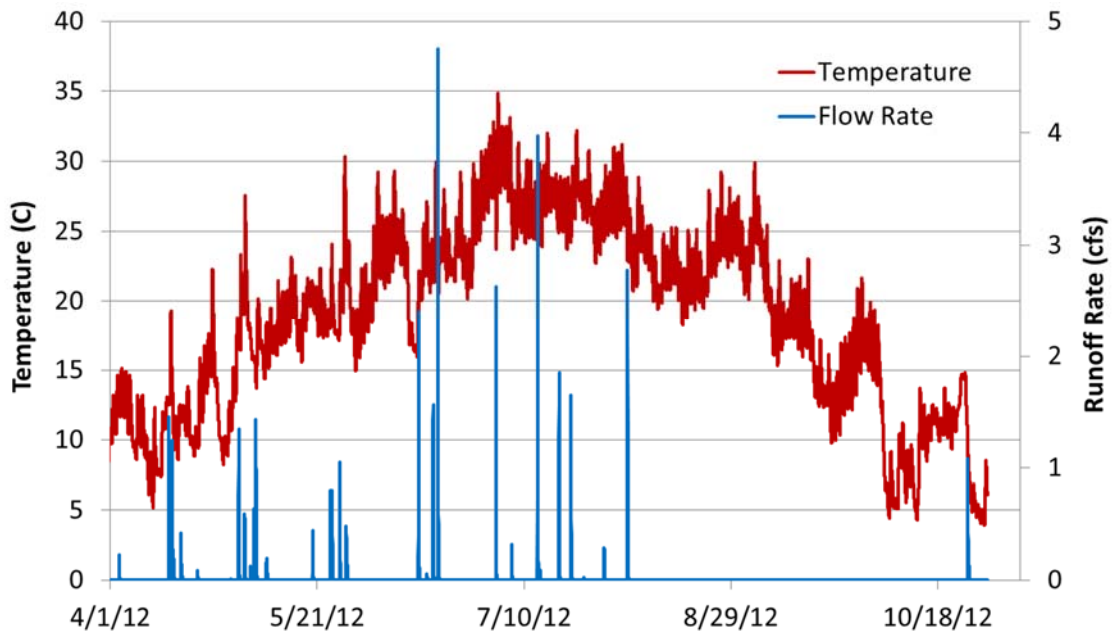


Figure 2.7. Simulated 15 minute time series of stormwater pond runoff input rate and temperatures for the Oak Glen stormwater pond in 2012, from the MINUHET model.

Stream Shading Analysis

Riparian shading is crucial in determining stream temperature, and specification of riparian shading in a stream temperature model is very important. In this study, LiDAR data were used to estimate the spatial variability of riparian shading along the modeled section of Brown's Creek, as follows:

- 1) The complete LiDAR point cloud was obtained for the watershed from the MnGeo archive (<http://www.mngeo.state.mn.us/chouse/elevation/lidar.html>).
- 2) Based on the point cloud, a DEM was constructed representing the top surface of the tree canopy.
- 3) The solar radiation analysis tool in ArcMap was used to calculate mean monthly solar radiation inputs to a series of 100 points along the main stem of Brown's Creek. This ArcMap tool essentially treats the tree canopy DEM as local topography, and determines whether each point in the stream is shaded or not for all sun angles in each day, and integrates the total solar radiation reaching each point over the analysis time period (1 month, in this case).
- 4) The solar radiation analysis tool does not correctly handle tree canopies that overhang the stream channel. Therefore, a second analysis was performed to quantify areas along Brown's Creek with overhanging tree canopies, mainly in section downstream of Stonebridge. Sections of the stream with full tree canopy coverage were assumed to be 90% shaded, i.e. only 10% of daily incoming solar radiation reaches the stream.

The results of steps 3) and 4) were combined, and a constant scale factor was applied. Since the LiDAR flights were typically made after leaf-off, the shading values based on LiDAR are typically underestimated. The resulting spatial distribution of riparian shading is shown in Figure 3.1.

Stream Temperature Simulation for Current Conditions

Using the climate, runoff, and baseflow inputs described above, stream temperature simulations were performed for 2012 and 2014, for April through October. The simulation period was chosen mainly based on the available climate station and stream temperature monitoring record. Within the available period-of-record, 2012 was selected because it represents a warmer and drier (lower flow) year whereas 2014 represents a cooler and wetter (higher flow) year. For May through September, 2012 was 1.4 °C higher in average temperature, with 22% (5.2 inches) less rainfall, compared to 2014. In its present form, the CE-QUAL model is restricted to open water conditions (no ice cover). Example stream temperature simulations for existing conditions in 2012 are shown in Figures 2.8 and 2.9, and for existing conditions in 2014 in Figures 2.10 and 2.11. Overall, temperature simulations were somewhat better in 2014, the wetter and cooler year. For daily time steps, the RMSE (root-mean-square error) of the simulations was about 1.3 °C in 2012 and 1.0 °C in 2014. The RMSE is a measure of the typical error in simulated temperature values versus observed temperatures, and is calculated as:

$$RMSE = \sqrt{\frac{\sum (T_s - T_o)^2}{n}}$$

where T_s and T_o are the simulated and observed temperature, respectively, and n is the number of temperature observations. The maximum daily temperature data in Figures 2.9 and 2.11 suggest that the model is over-predicting maximum temperatures on some wet days, particularly in 2014. This could be due to the assumptions made in the routing of stormwater (directly vs. indirectly connected), limitations in the MINUHET simulations of runoff temperature and flow rates from impervious areas, or in the CEQUAL model itself (heat routing during highly transient storm flow).

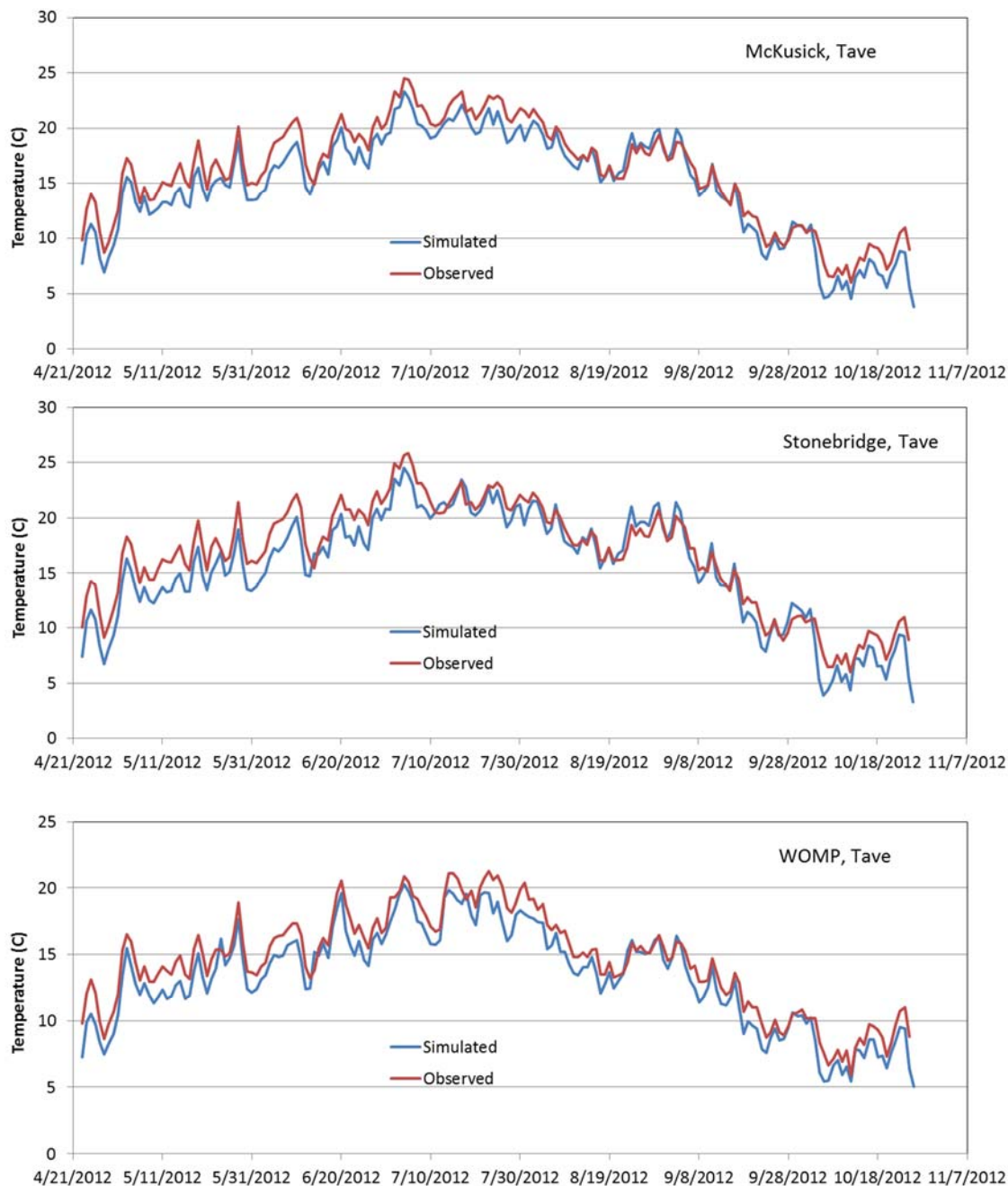


Figure 2.8. Time series of simulated and observed daily average stream temperatures in 2012 at the WOMP, Stonebridge, and McKusick monitoring stations.

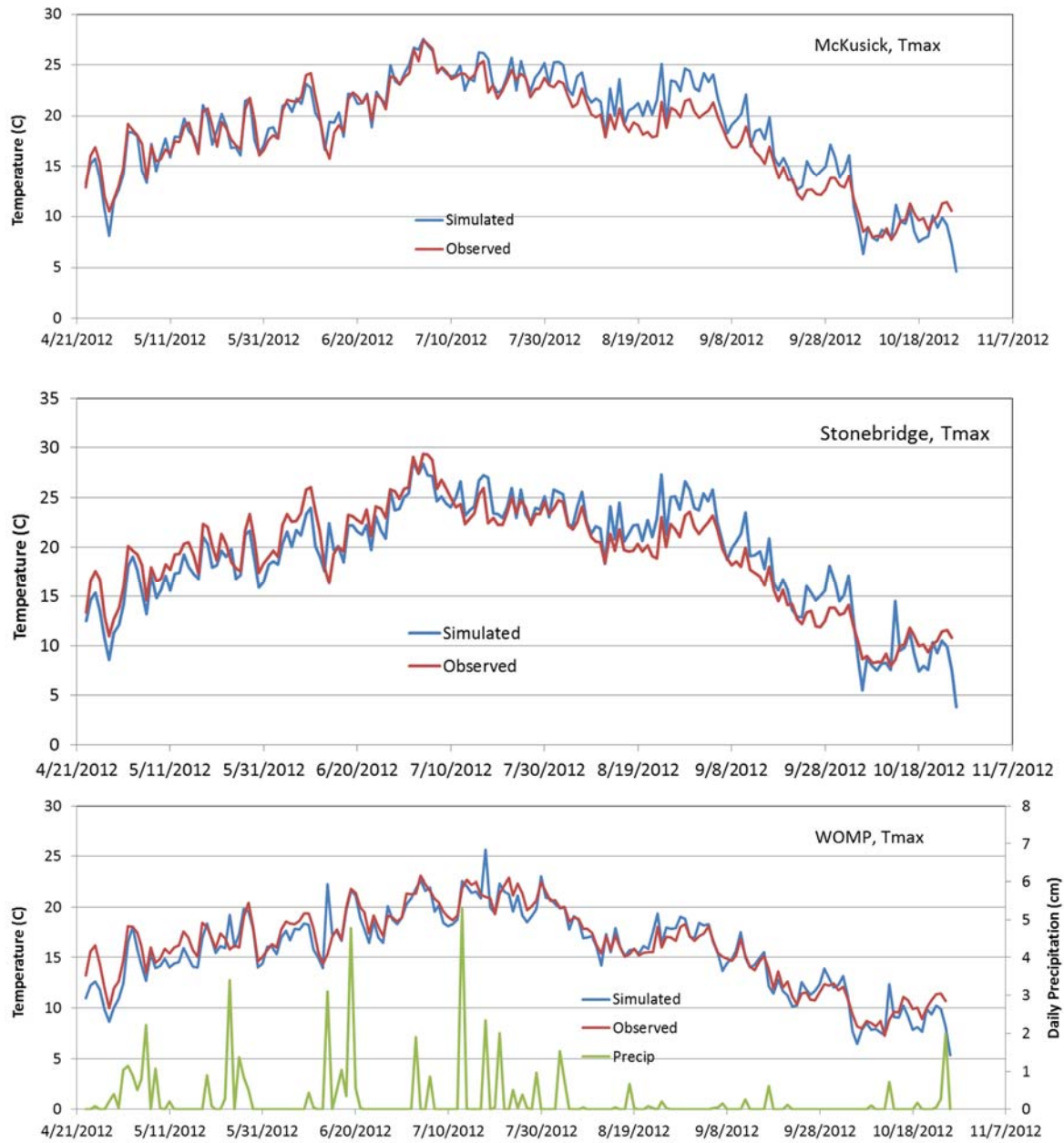


Figure 2.9. Time series of simulated and observed daily maximum stream temperatures in 2012 at the WOMP, Stonebridge, and McKusick monitoring stations. Precipitation data from the BCWD weather station is also shown with the WOMP data.

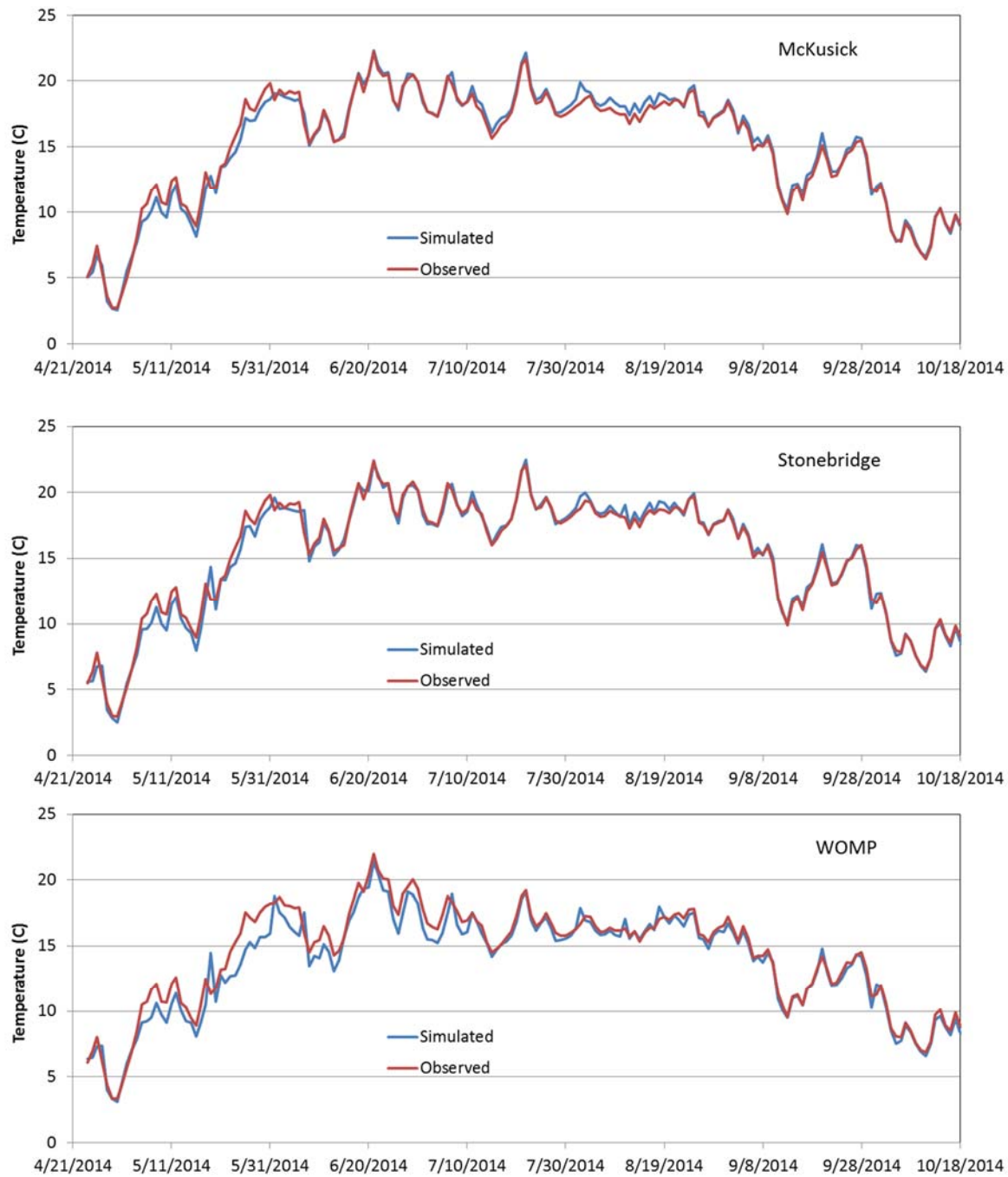


Figure 2.10. Time series of simulated and observed daily average stream temperatures in 2014 at the WOMP, Stonebridge and McKusick monitoring stations.

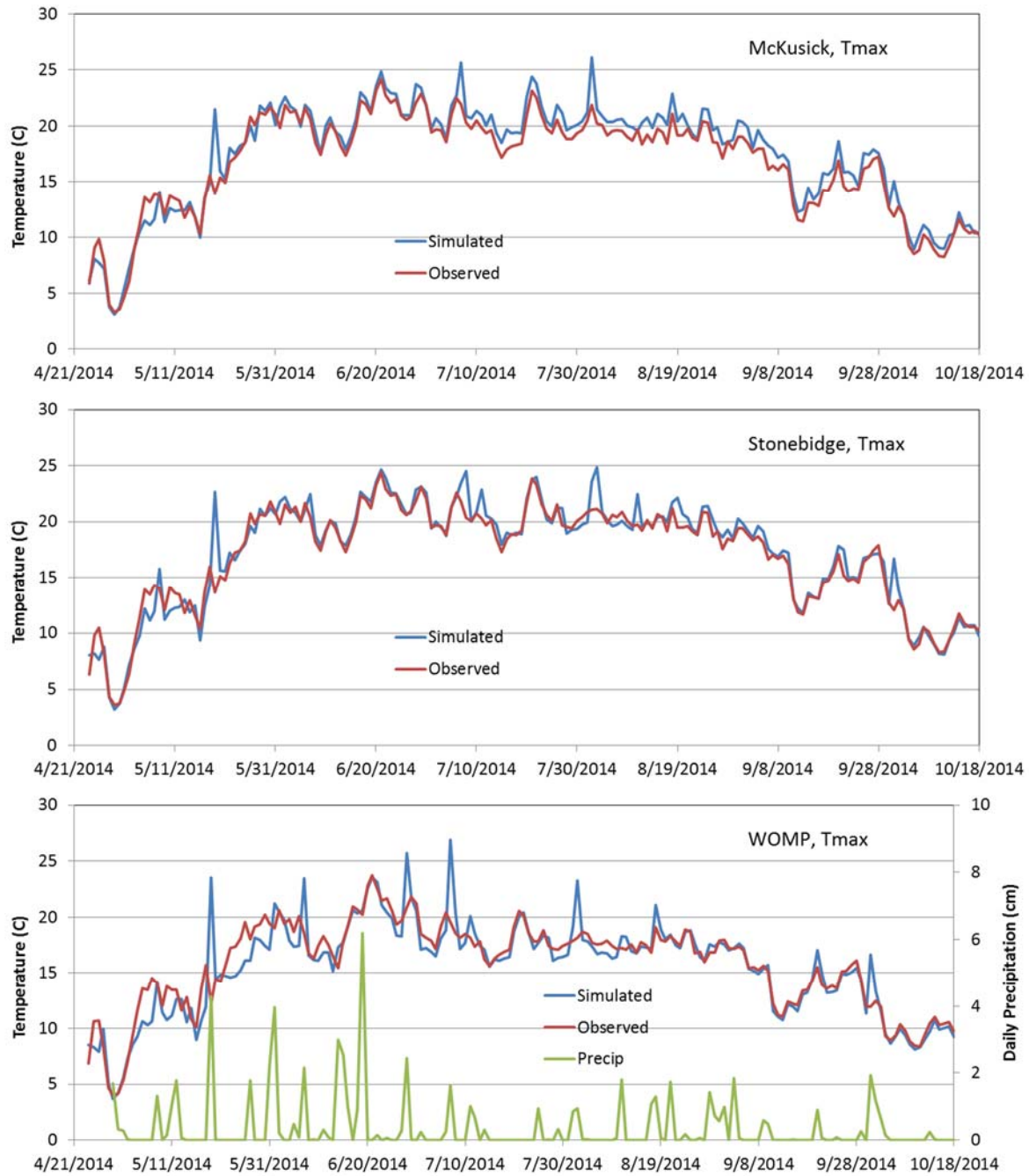


Figure 2.11. Time series of simulated and observed daily maximum stream temperatures in 2014 at the WOMP, Stonebridge and McKusick monitoring stations. Precipitation data from the BCWD weather station is also shown with the WOMP data.

III. Stream Temperature Scenarios

The following plots summarize preliminary simulations for several temperature mitigation scenarios, using the CE-QUAL W2 model with 2012 and 2014 climate and flow conditions:

- 1) Shade mitigation I, where a minimum shading level of 50% is established (see Figure 3.1)
- 2) Shade mitigation II, where a minimum shading level of 75% is established (see Figure 3.1)
- 3) Disconnect the stormwater ponds at the Oak Glen golf course.
- 4) Increase baseflow between McKusick/Neal Ave and Stonebridge, giving a 15% increase in total baseflow in Brown's Creek.

Example time series of simulated stream temperature for current conditions (2012) and for the shade mitigation II scenario are shown in Figure 3.2. The Stonebridge monitoring location saw the largest temperature reduction for the shading scenario, because it is near the downstream end of a reach with low shading in current conditions (Figure 3.1). For 2012, the shading scenarios give reductions in monthly mean stream temperature on the order of 0.5 to 1 °C over the entire modeled section of the main stem (WOMP to Manning Avenue), as shown in Figure 3.3. The pond mitigation scenario gave almost no reduction in mean monthly temperatures, with reductions on the order of 0.01 °C. The total number of hours of temperature exceedance ($T > 18.3$ °C) showed relatively little improvement in July for all scenarios (Figure 3.4), because stream temperatures still substantially exceeded the threshold, even with improved shading. More reduction in exceedance hours was predicted for August (Figure 3.4), because the nominal stream temperatures were closer to the threshold value in the baseline condition. Similar results were obtained for analysis of the number of exceedance days per month (Figure 3.5).

The poor effectiveness of the pond mitigation scenario in 2012 is examined further in Figures 3.6 and 3.7. The mean monthly temperature of both unmitigated surface runoff and pond discharges exceed the mean stream temperature by 2-3 °C in July and August (Figure 3.6), however, runoff volumes in 2012 were a relatively small fraction of total stream discharge in 2012 (3-10%), so that the overall thermal impact of surface runoff and pond inputs was minimal in 2012.

A similar set of scenarios were run for 2014. Compared to 2012, 2014 was warmer in May, June, and July, and wetter than 2012 in June and August (Figure 3.8). Application of the shading scenarios I and II gave about 0.25 and 0.5 °C reduction in mean water temperatures in July and August, respectively (Figure 3.9). Comparing Figure 3.3 (for 2012) and Figure 3.9 (for 2014), July water temperatures were about 2 °C lower in 2014, so that the shading scenarios gave less reduction in temperature for 2014 compared to 2012. In August, air and water temperatures were more similar in 2012 and 2014, however, August was wetter in 2014, with higher streamflow (2.7 cfs in 2012, 6.0 cfs in 2014). It is therefore likely that the shading scenarios gave relatively little reduction in temperature in August 2014 because of higher streamflow conditions.

The effect of the mitigation scenarios on the monthly duration of temperature exceedances (>18.3 °C) in 2014 is illustrated in Figure 3.10. As with mean water temperatures, the reductions in exceedance

duration provided by the mitigation scenarios are modest. Unlike 2012, the pond mitigation scenario does give a measurable reduction in the number of exceedance hours in August 2014. However, the effect of the mitigation scenarios on the number of exceedance days (a day with at least 1 hour of temperature exceedance) is very minimal (Figure 3.11).

Table 3.1. Summary of simulated stream temperature changes in 2012 (warm/dry) and 2014 (cool/wet) for the four mitigation scenarios. The changes listed are the largest changes in temperature along the modeled section of Brown's Creek, between the WOMP station and Manning Avenue.

	Year	Shade Mitigation 1	Shade Mitigation 2	Pond Disconnect	Baseflow Mitigation
Change in July Mean Temperature (°C)	2012	-0.52	-1.1	0.0	-0.29
	2014	-0.24	-0.51	-0.02	0.0

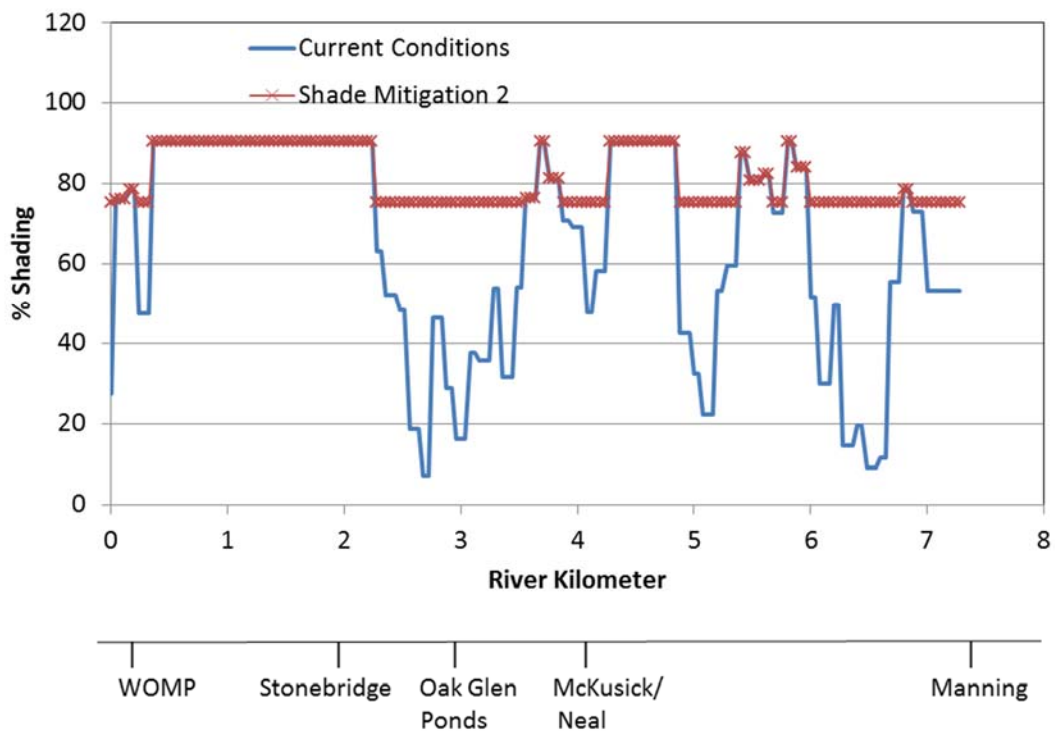
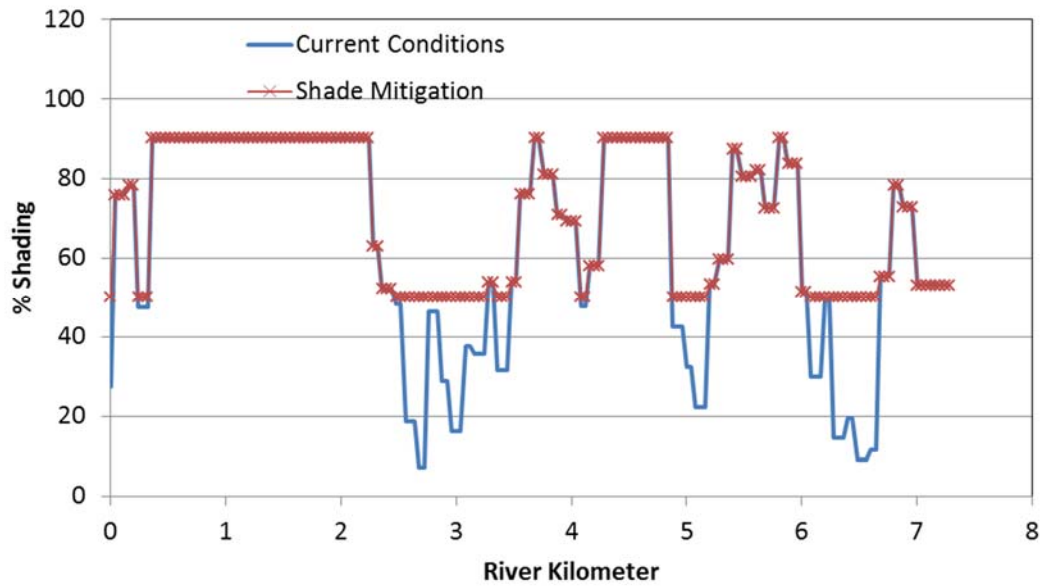


Figure 3.1. Distribution of riparian shading along the main stem of Brown's Creek for current conditions and two mitigated shade scenarios. 100% shading means the reach is fully shaded, with no solar radiation reaching the water surface.

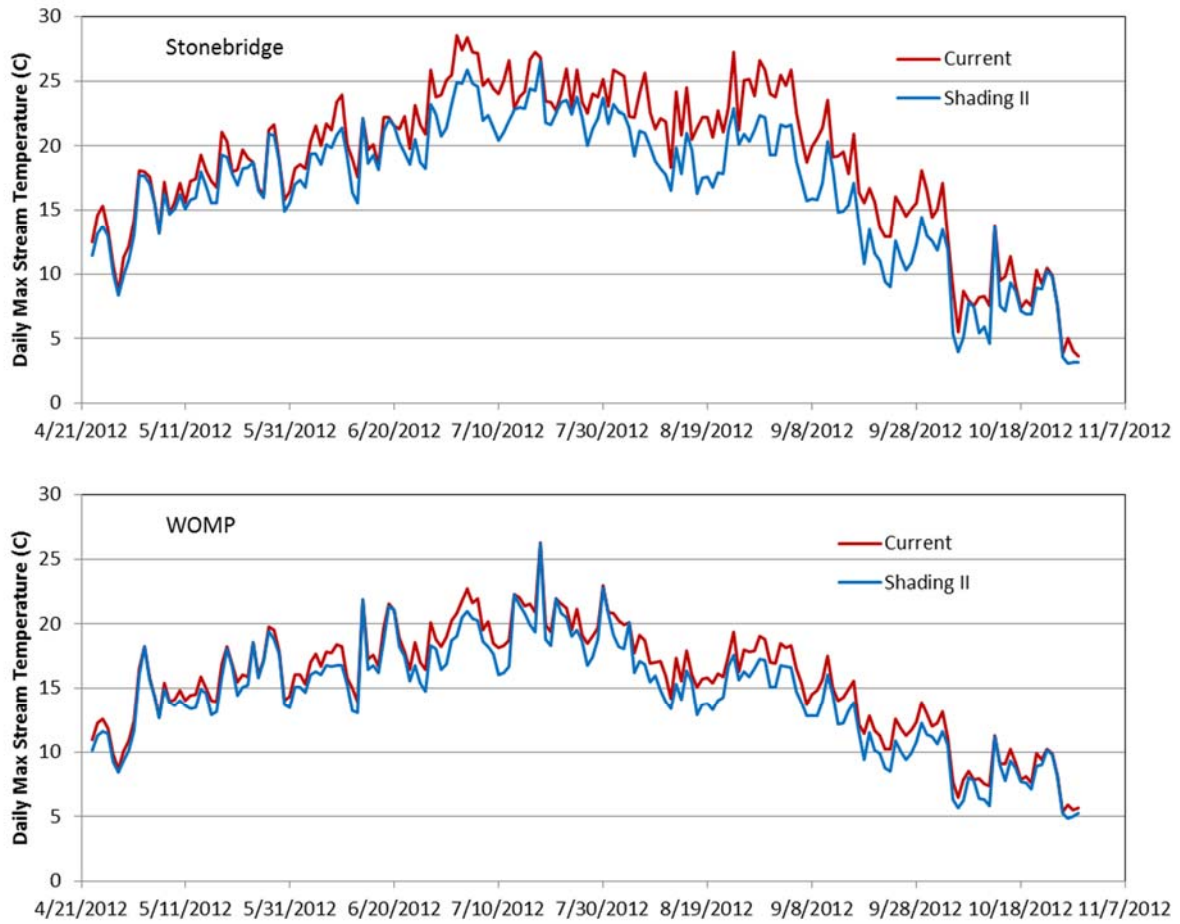


Figure 3.2. Simulated time series of daily maximum water temperature in 2012 at the Stonebridge and WOMP monitoring site for current conditions and for the second shading scenario.

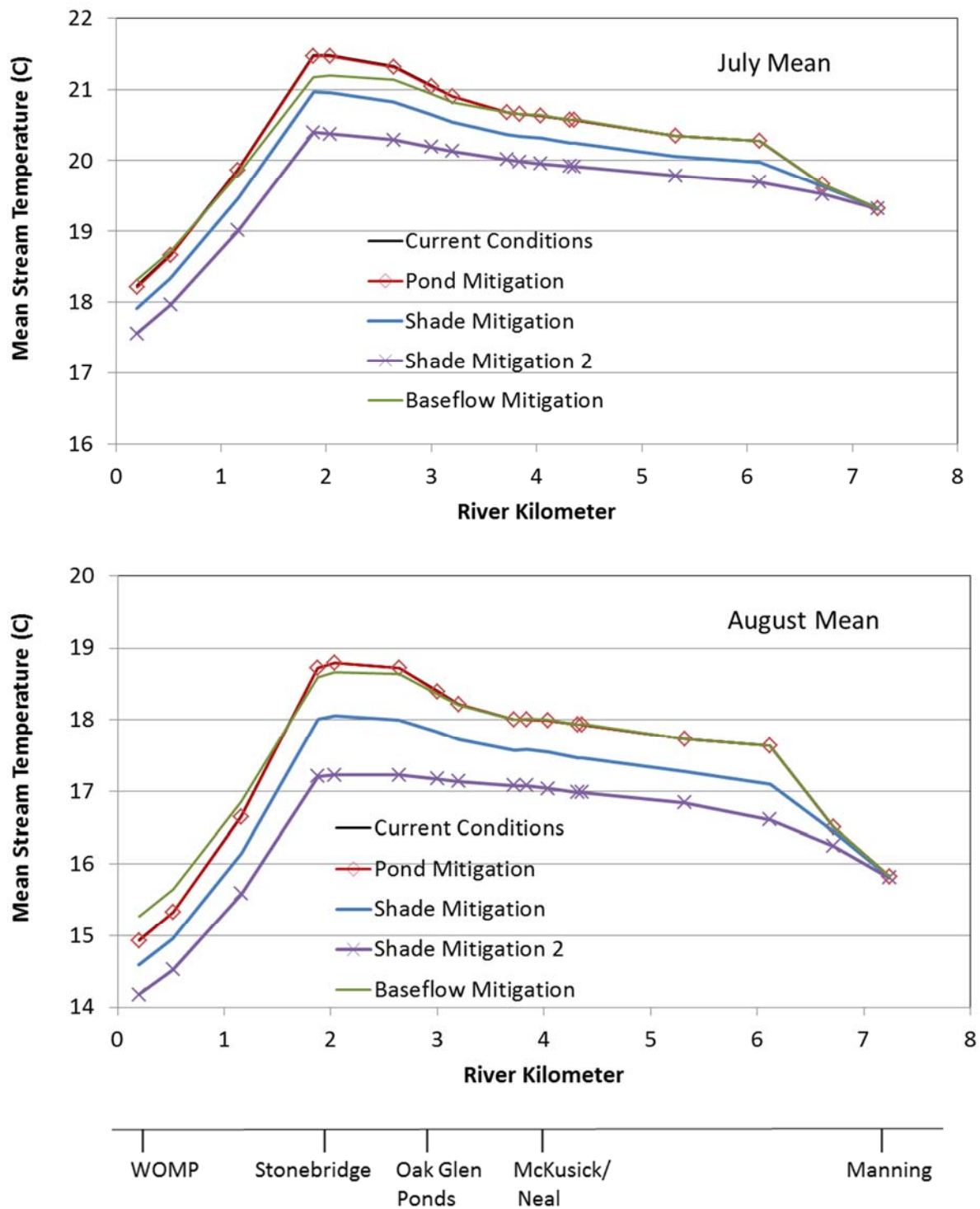


Figure 3.3. July and August mean water temperature vs. position for July and August 2012, current conditions, the two shading mitigation scenarios (Figure 3.1), and the pond mitigation scenario. The data for current conditions and the pond mitigation scenario lie on top of each other.

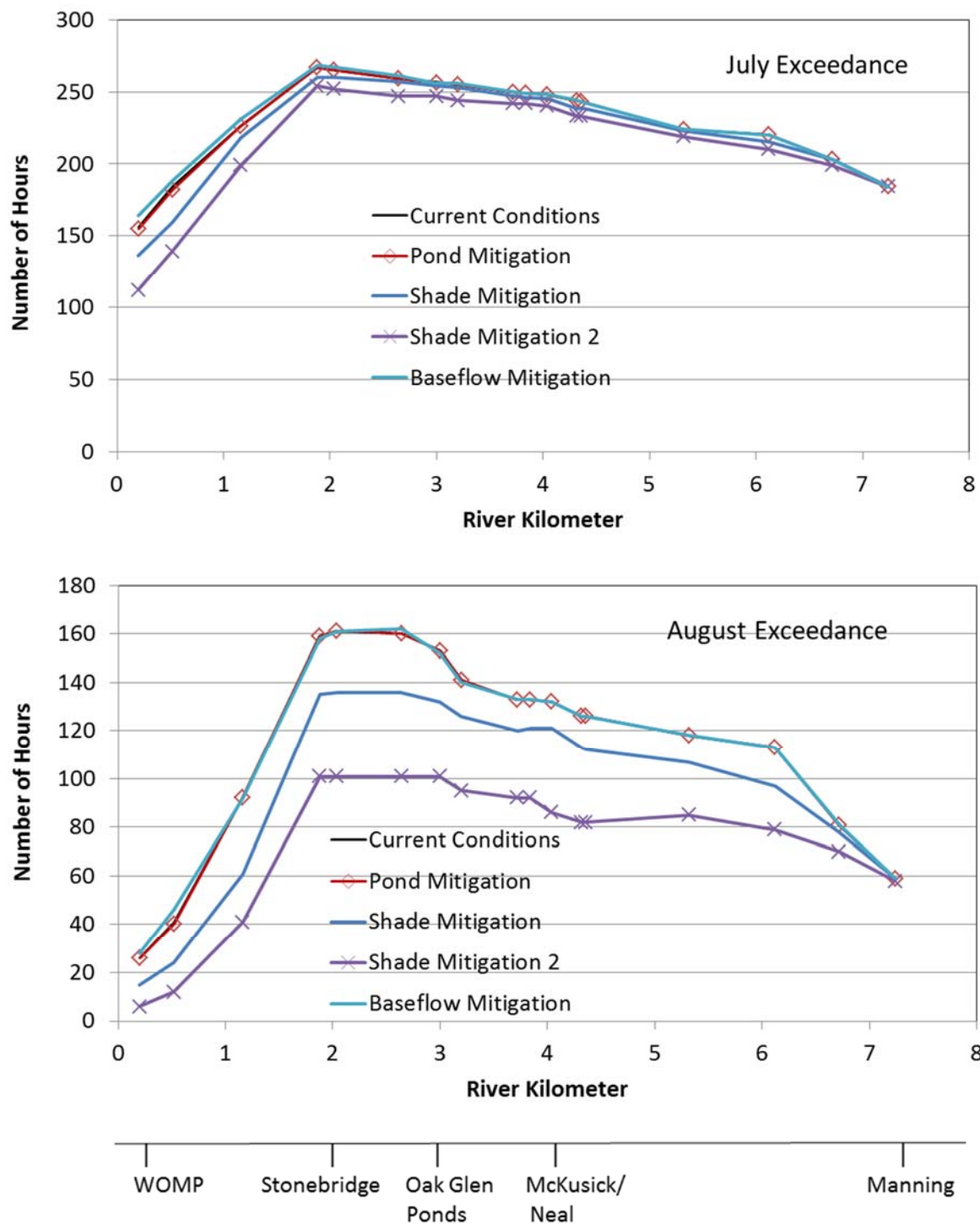


Figure 3.4. Total number of exceedance hours vs. position for July and August 2012, current conditions, the two shading mitigation scenarios (Figure 3.1), and the pond mitigation scenario. The data for current conditions and the pond mitigation scenario lie on top of each other.

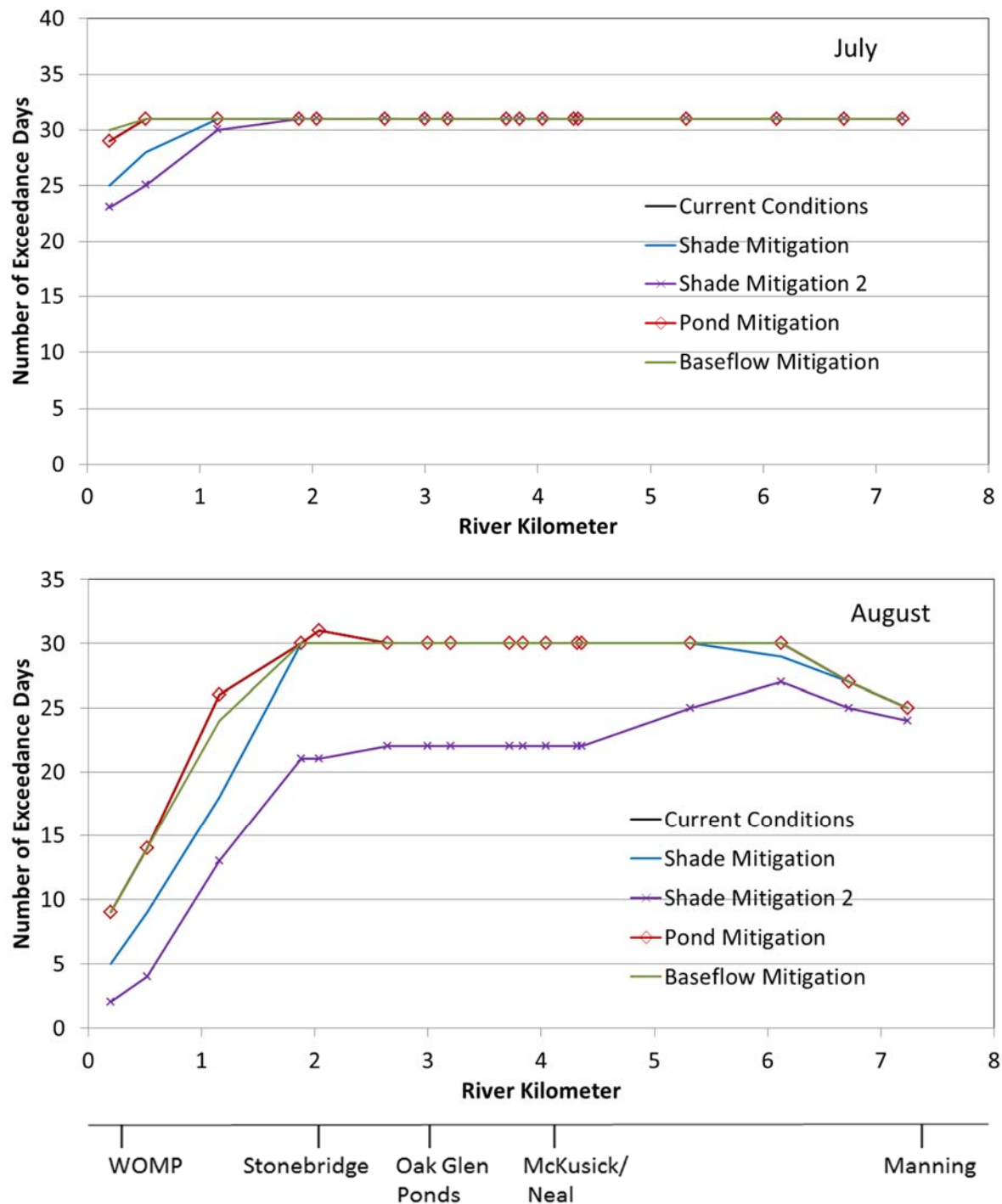


Figure 3.5. Total number of exceedance days vs. position for July and August 2012 current conditions, the two shading mitigation scenarios (Figure 3.1), and the pond mitigation scenario. An exceedance day is a day when the stream temperature exceeds 18.3 °C for at least 1 hour. The data for current conditions and the pond mitigation scenario lie on top of each other.

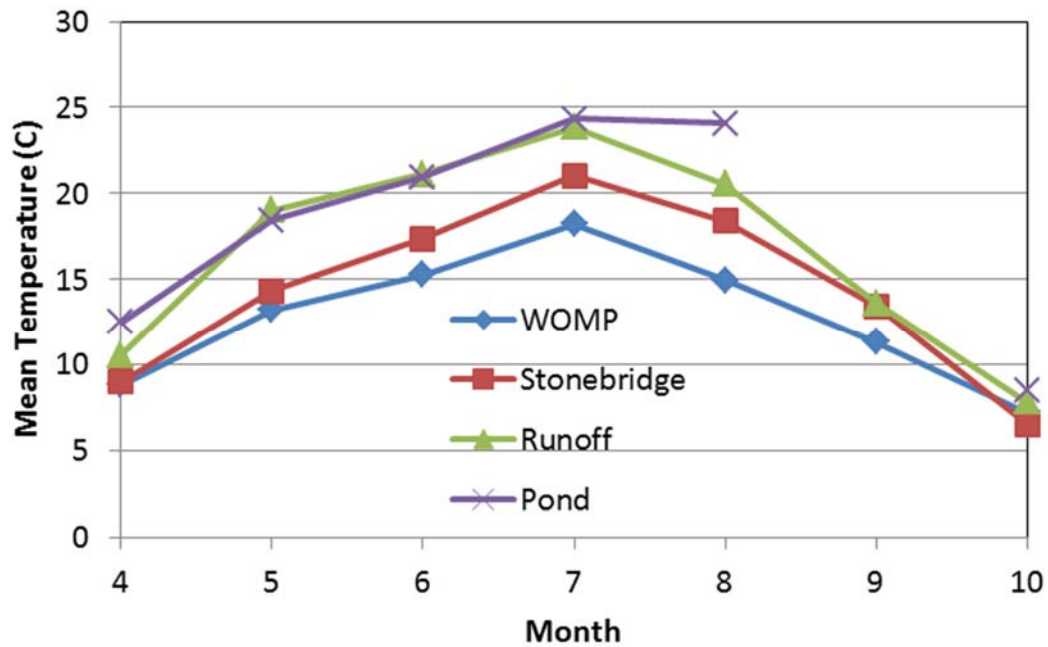


Figure 3.6. Monthly average stream temperature in comparison to monthly average surface runoff and pond input temperatures. Runoff and pond outflow temperatures are volume weighted. There is no mean pond temperature in September, because there was no discharge in the pond simulations.

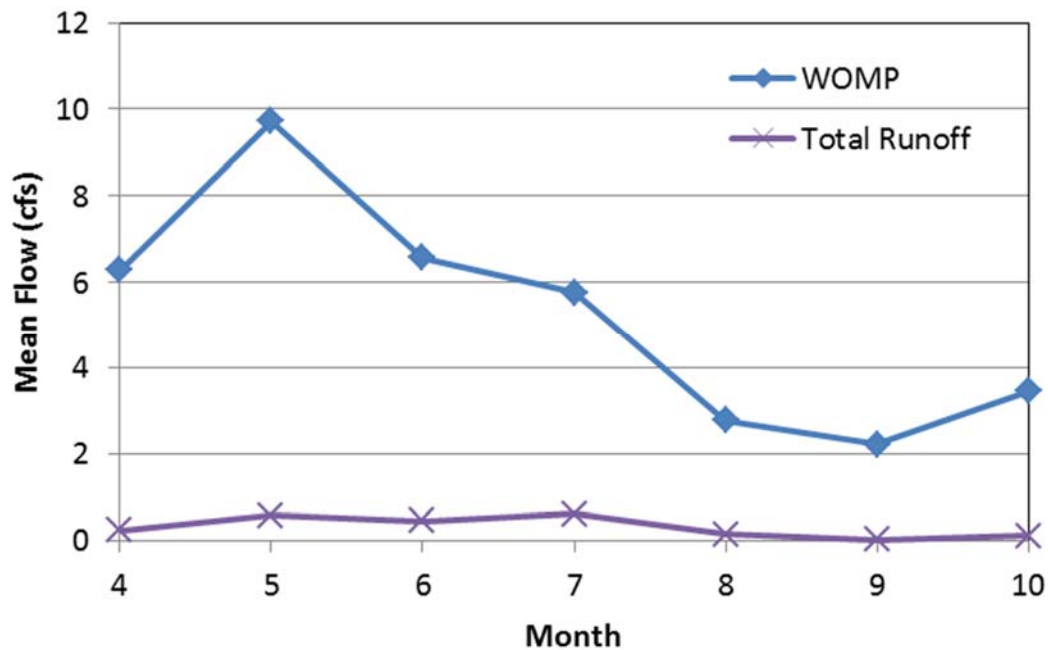


Figure 3.7. Monthly average stream flow at the WOMP station in comparison to monthly average runoff inputs rates (including ponds).

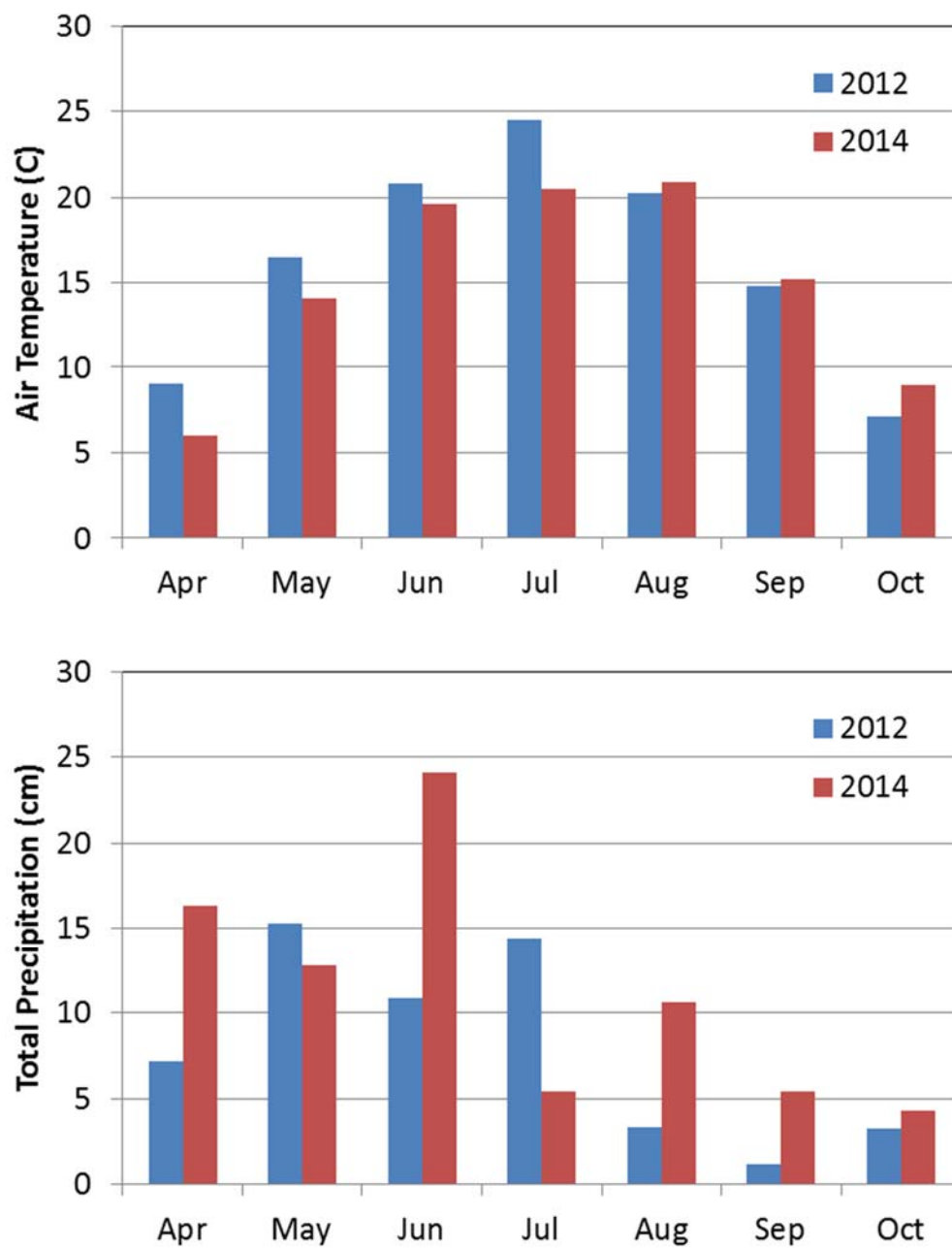


Figure 3.8. Summary of monthly air temperature and precipitation in the two study years, 2012 and 2014.

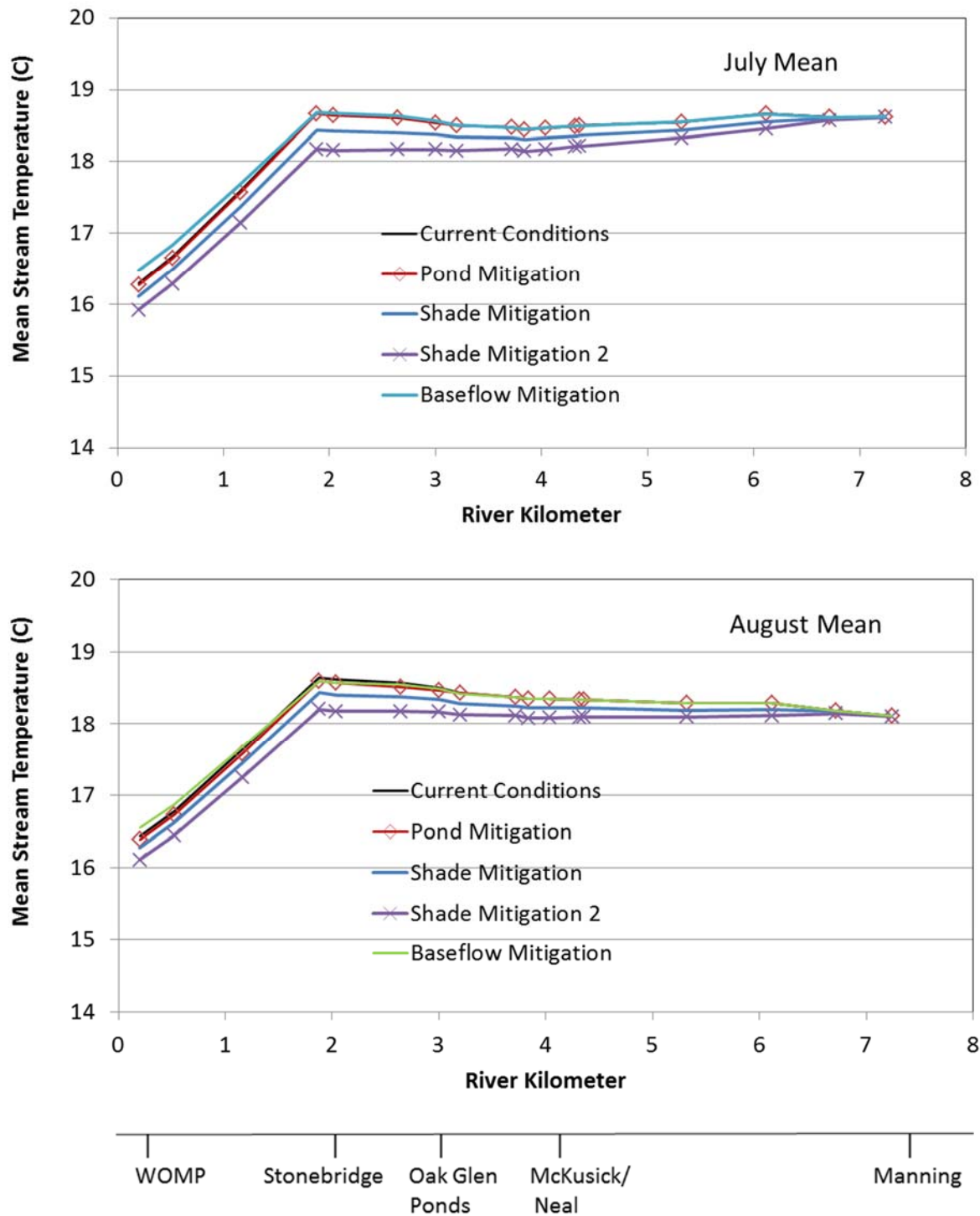


Figure 3.9. July and August mean water temperature vs. position for July and August 2014, for current conditions, and the four mitigation scenarios .

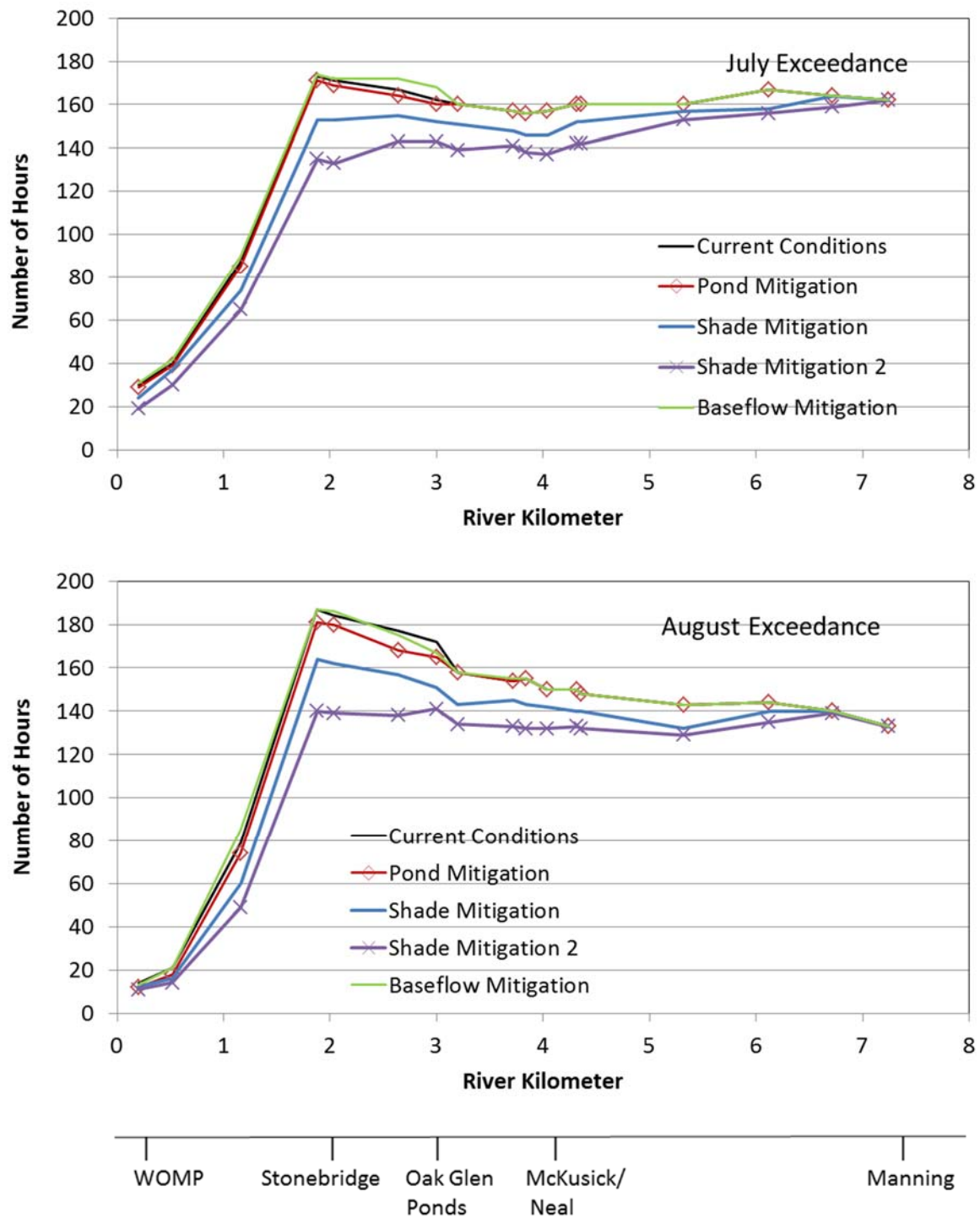


Figure 3.10. Total number of exceedance hours ($T > 18.3^{\circ}\text{C}$) vs. position for July and August 2014, current conditions, and the four mitigation scenarios.

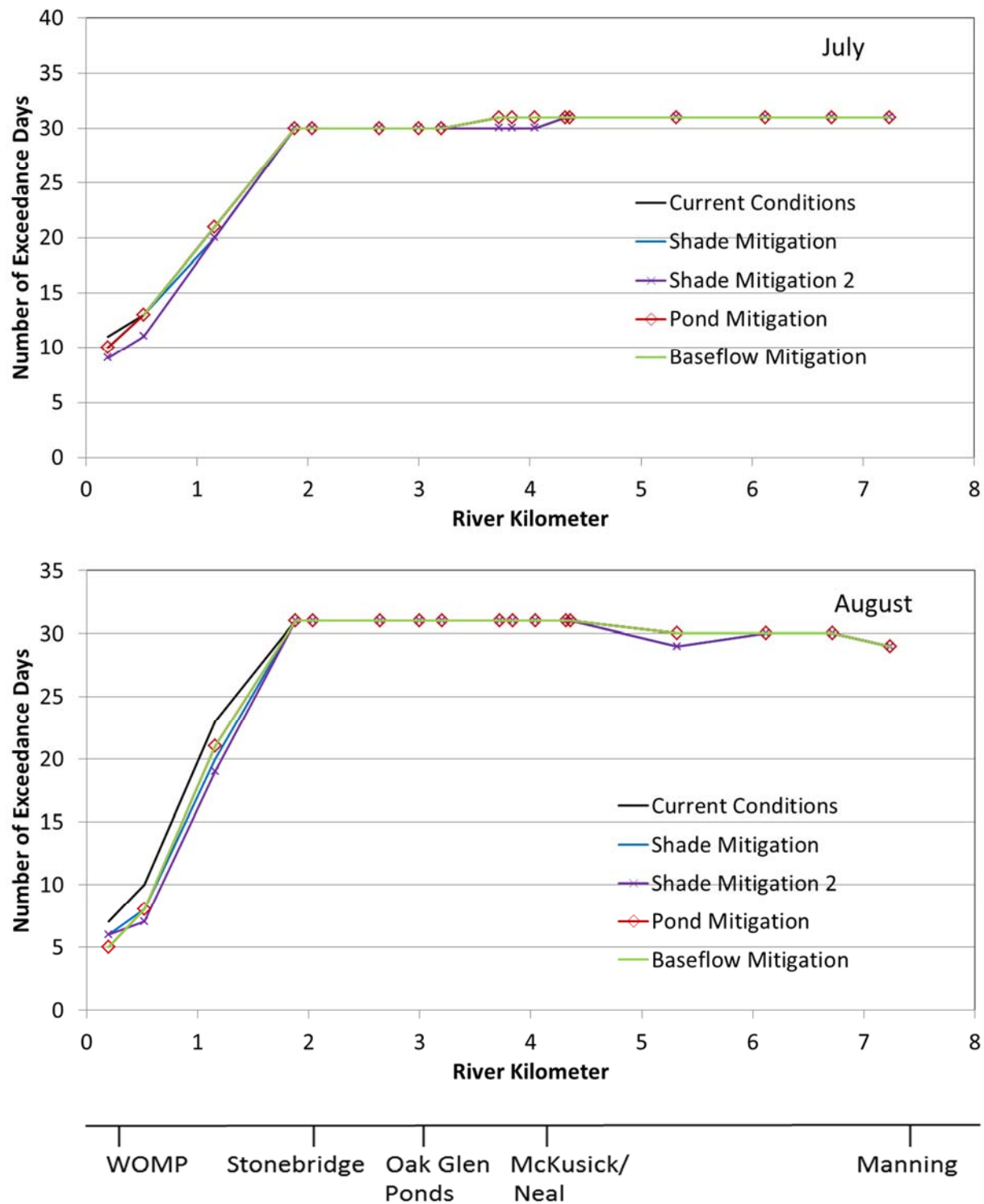


Figure 3.11. Total number of exceedance days vs. position for July and August 2014, current conditions, and the four mitigation scenarios. An exceedance day is a day when the stream temperature exceeds 18.3 °C for at least 1 hour.

IV. Conclusions and Recommendations

Model Limitations

- The riparian shading analysis performed in this study was based on LiDAR, and focused on tree canopy coverage. LiDAR does not work well for characterizing shading at smaller scales, e.g. tall grass shading a narrow stream channel. It may be appropriate to evaluate reaches of interest with field surveys to better determine local shading conditions, as suggested in Figure 4.1. The LiDAR data for this area was flown in 2011, and therefore does not capture recent shade augmentation work.
- The model uses a typical stream width for each channel segment, and therefore does not include local channel features such as wide bends and beaver ponds. While local stream widening over short distances is not expected to significantly change stream temperature, beaver ponds can have a significant affect both on flow and temperature downstream of the pond, and would make a worthwhile addition to the model in the future.
- The model included surface runoff inputs at 10 points and inputs from ponds at the golf course and Millbrook pond. Inputs from individual wetlands were not explicitly considered, but were incorporated as part of the baseflow inputs. Future work could include the local thermal impact of particular wetlands, such as the McKusick wetland. Field data taken in 2015 suggest that spatial distribution of baseflow inputs to Brown's Creek assumed in model may not capture seasonal dynamics in local areas.

Scenario Analysis Results

Several types of mitigation scenarios were examined using the stream temperature model. Increasing riparian shading or increasing baseflow reduces stream temperature on warm, dry days, whereas disconnecting stormwater inputs mainly impacts stream temperature on wet days. Since, in general, high stream temperatures tend to be during warm, dry days in Brown's Creek and other marginal coldwater streams, riparian shading and baseflow mitigation generally offer more potential for reducing the number of days with high stream temperature. Baseflow inputs from a stormwater pond receiving groundwater pumping (Oak Glen East) are a source of heat input during stream baseflow periods, but this input, by itself, had negligible effect on stream temperature ($< 0.1^{\circ}\text{C}$) for the assumed pumping rate (0.03 cfs).

Increasing riparian shading gave measureable decreases in mean stream temperature of up to 1.1°C , with more benefit seen in the warmer/drier year (2012). The shading scenario giving a decrease of 1.1°C is a substantial effort, with shading mitigation over about 3 km of channel length (see Figure 4.1). It may be worthwhile to consider the benefit of a more localized shading mitigation effort, with a prioritization by 1) what reaches are highest priority to restore for trout habitat and 2) what reaches are most suitable for riparian shading mitigation, based on ownership, channel width and orientation, etc.

The baseflow mitigation scenario, which represents a partial restoration of flow from the diversion structure and an increase in overall baseflow in Brown's Creek of about 15% (0.3 to 1.2 cfs, seasonally

varying), gave a modest temperature decrease in 2012 (0.3 °C in mean July temperature) and no change in 2014. These temperature changes are relatively uncertain, because the temperature of the additional baseflow depends on the details of the surface and subsurface flow paths that are established to reconnect this baseflow to the main stem. While this temperature reduction is lower than that given by the shading scenarios, there are other benefits to increasing baseflow in Brown's Creek. Increasing the watershed area that contributes baseflow to Brown's Creek should make the flow more robust in the face of variable climate and regional groundwater demands.

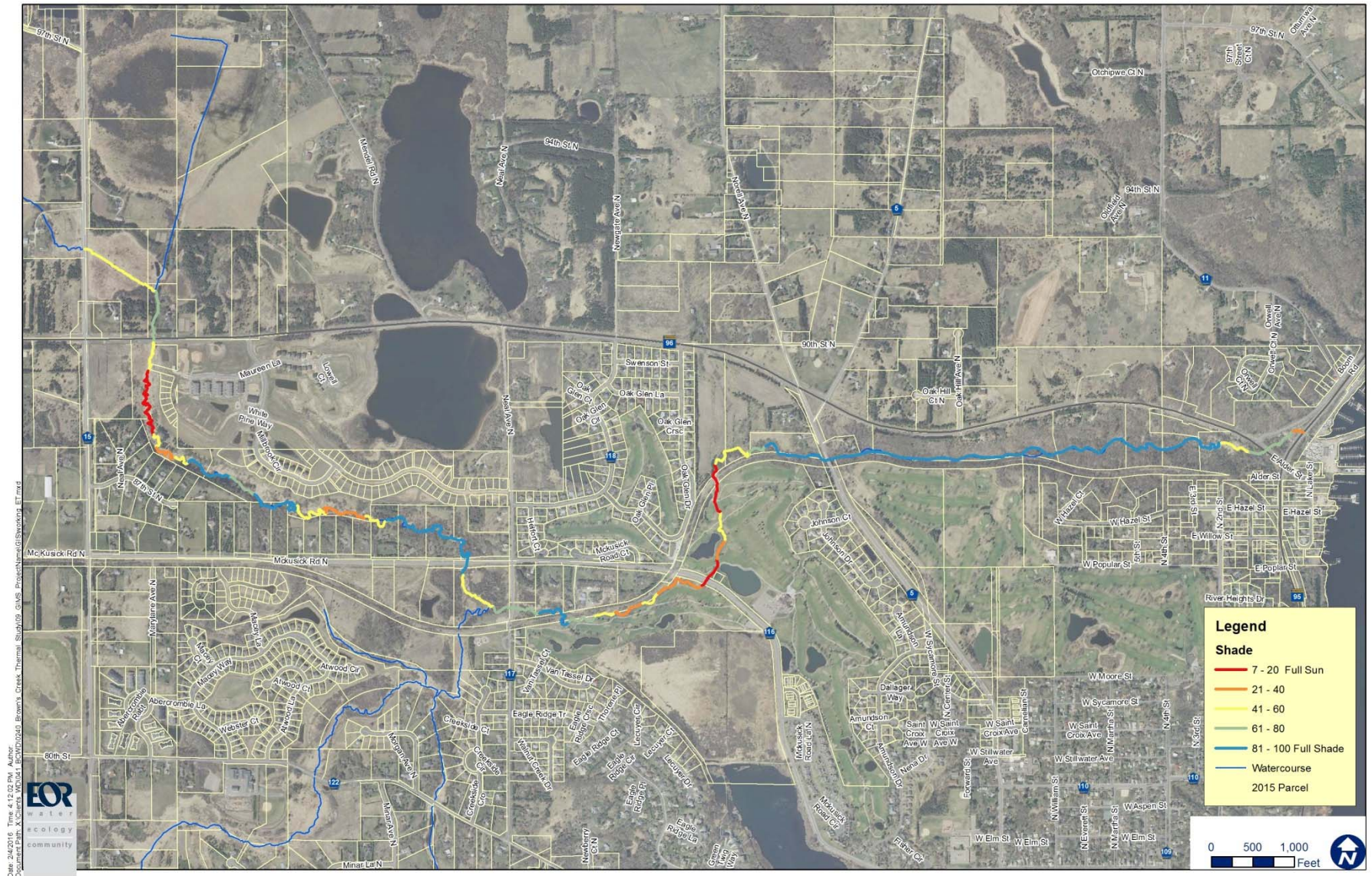
Disconnecting the ponds in the Oak Glen area gave essentially no temperature reduction in 2012 and only a small temperature reduction (<0.1 °C) in 2014. Although pond discharges are at a relatively high temperature, this reach is already impacted by low shading. If riparian shading were to be improved in this area of Brown's Creek, the thermal impact of the stormwater ponds may be more noticeable. An in-stream pond (e.g. a beaver pond) has more potential for increasing stream temperature compared to an off-line stormwater pond, because an in-stream pond adds heat to the stream during both dry and wet weather. One of the Oak Glen ponds may discharge during dry weather, due to groundwater pumping, however, based on the rates that were measured in 2014 (~ 0.02 cfs), the temperature impact of this discharge on Brown's Creek is likely minimal (<0.1 °C).

Future Monitoring Priorities

A broad array of monitoring data were used in this the project to calibrate and verify the stream temperature model. Monitoring efforts should be continued in the future, to further characterize baseflow sources and to enable trend analysis in stream flow and temperature.

- 1) In-stream flow and temperature monitoring should be continued at existing sites (WOMP, Stonebridge, Highway 15/Manning) to build a long-term record and enable trend analysis of flow rates and water temperatures.
- 2) Additional temperature monitoring at sites of interest, e.g. wetland and stormwater inputs and beaver ponds. Wherever possible, temperature monitoring should be combined with flow monitoring, to enable better estimates of thermal impact.
- 3) Based on the limitations identified in the LiDAR-based riparian shading analysis, additional in-situ shading measurements should be taken in reaches where some shading may be provided by tall grass and small trees. The restored reach in the Oak Glen golf course is a good candidate for such a study.
- 4) Groundwater and baseflow continues to be a data need for Brown's Creek. The existing gaging sites can provide long term records for trend analysis of baseflow, but the seasonal and spatial variability of baseflow inputs is still not well characterized. Pairing piezometer measurements with a means to measure the corresponding flow source rates would be an effective method to characterize baseflow sources.
- 5) The BCWD climate station provided valuable information on local precipitation, air temperature, and solar radiation in the watershed. Continued operation of this station in the future will be helpful both for any additional modeling work, and for trend analysis of flow and temperature.

Figure 4.1. Recommendations for thermal shading based upon tree canopy coverage



References

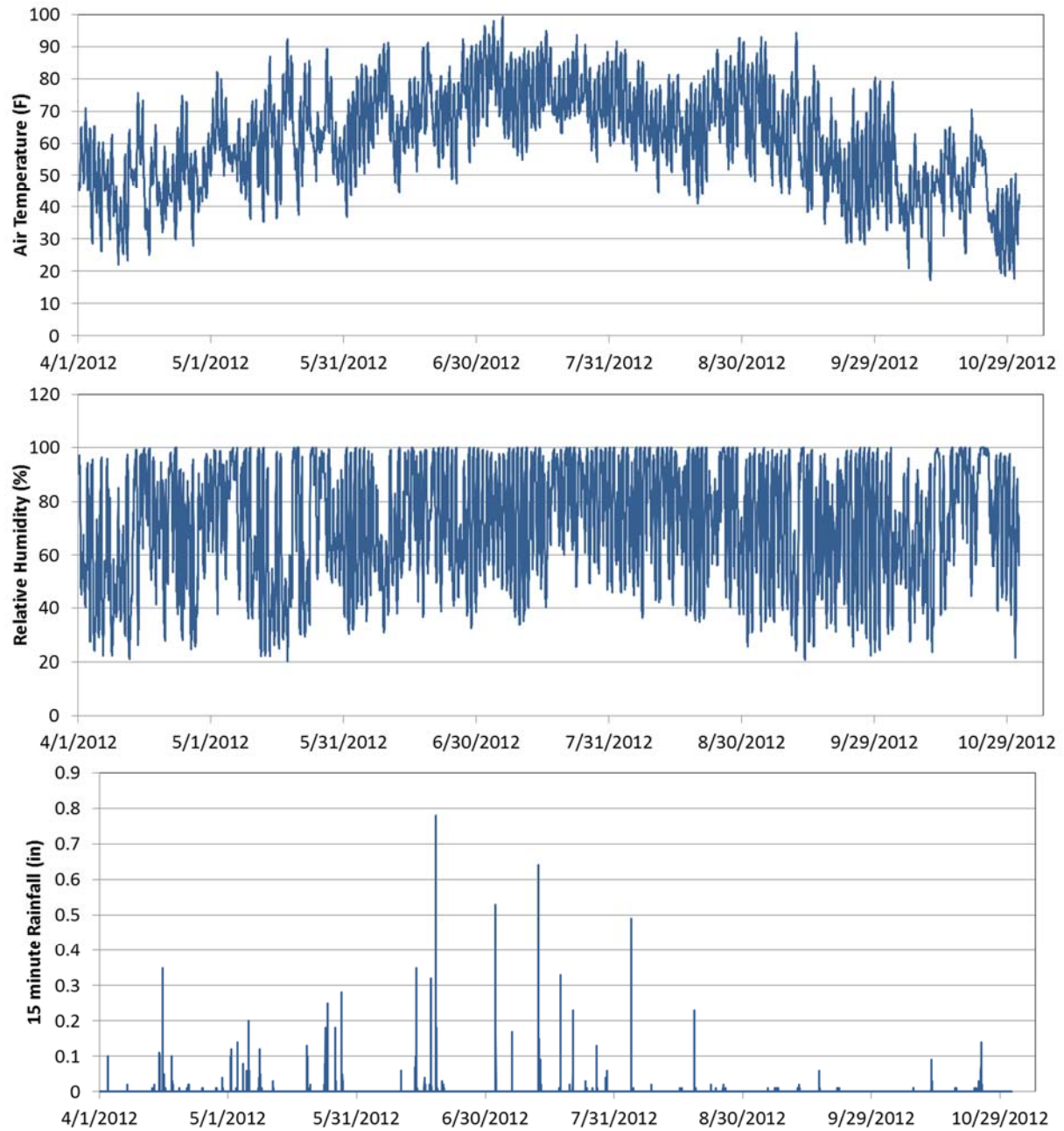
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Herb, W.R., Mohseni, O., and H.G. Stefan, 2007. A model for mitigation of surface runoff temperatures by a wetland basin and a wetland complex, St. Anthony Falls Laboratory Report 499, 34 pp.

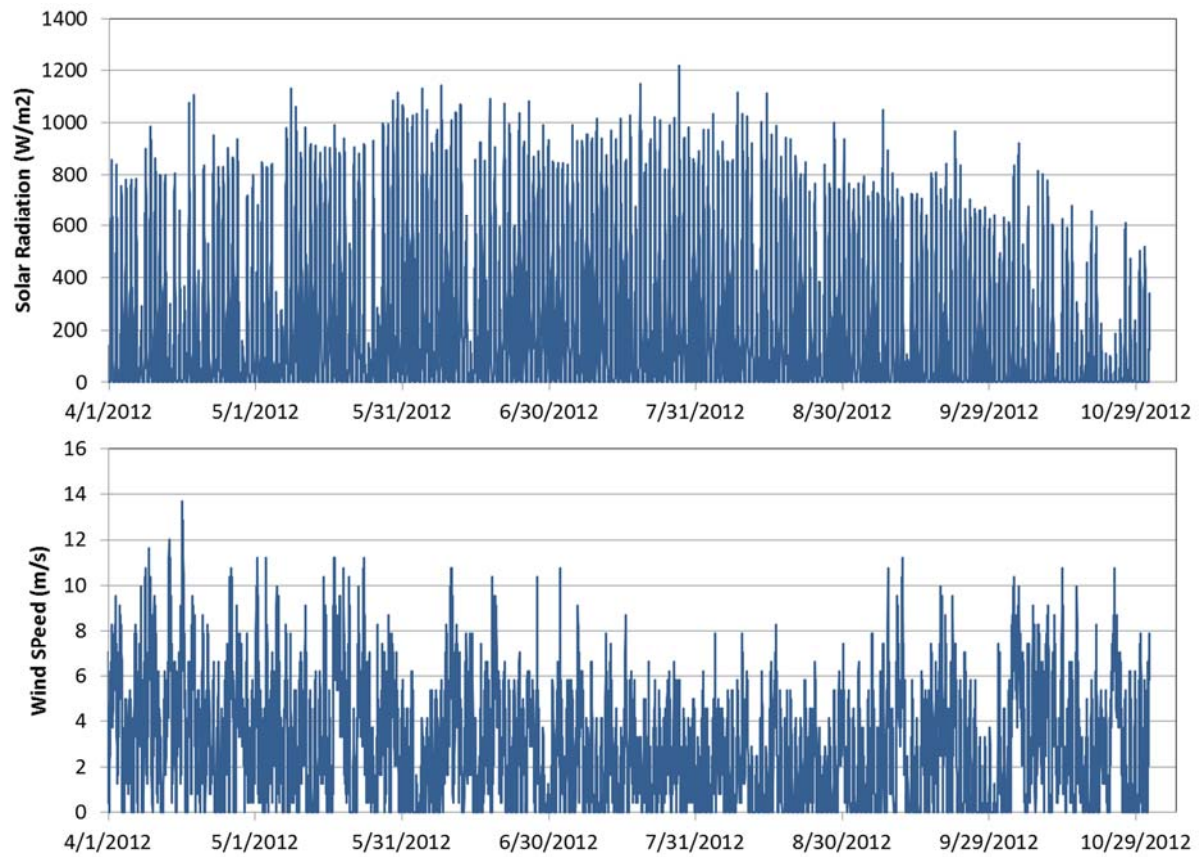
Herb, W.R., Janke, B., Mohseni, O., and H.G. Stefan, 2009. MINUHET (Minnesota Urban Heat Export Tool): A software tool for the analysis of stream thermal loading by urban stormwater runoff, St. Anthony Falls Laboratory Report 526, 44 pp.

Appendix I. Climate Data Inputs for the Stream Temperature Simulations in 2012 and 2014.

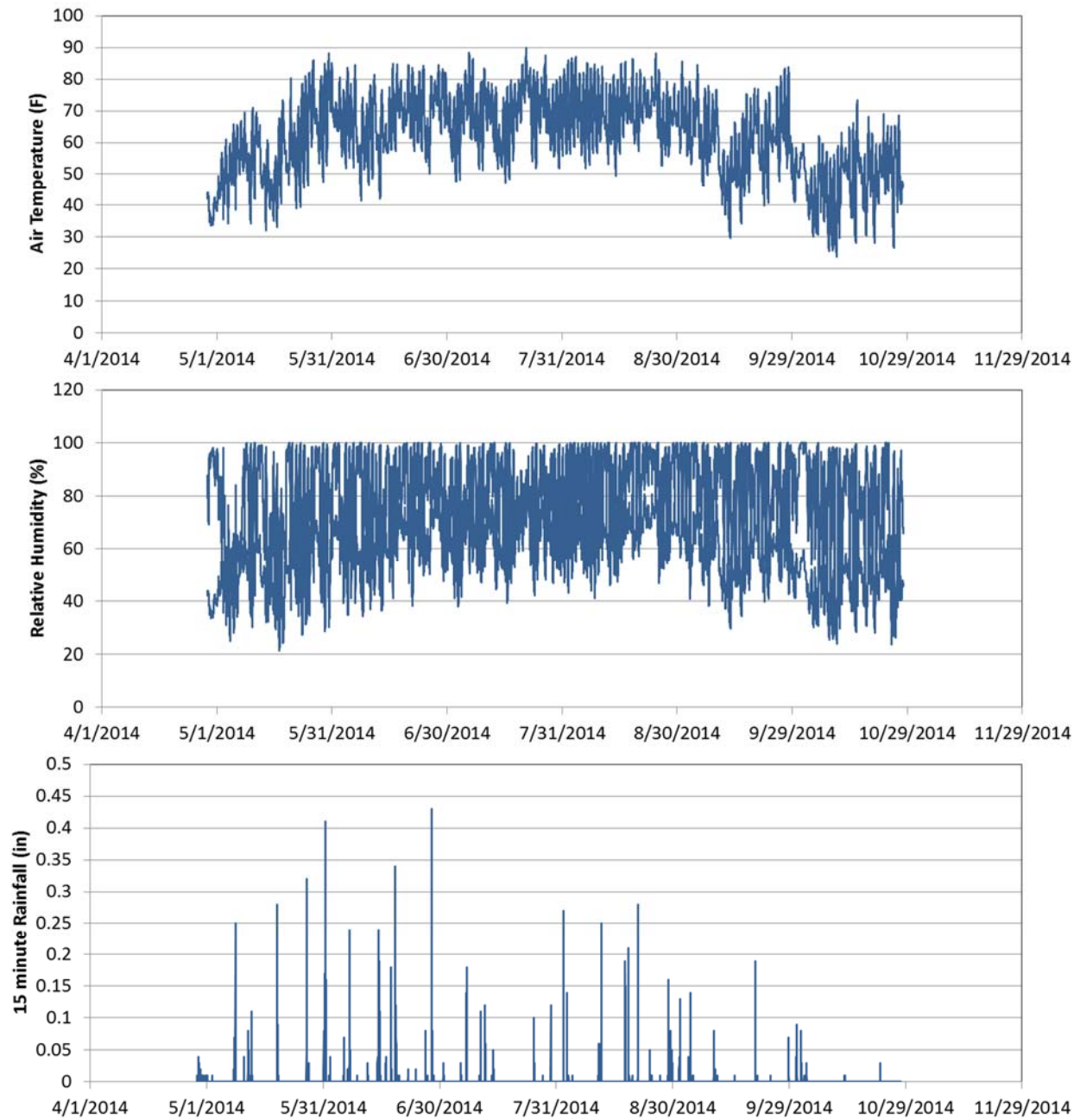
2012 Climate Data



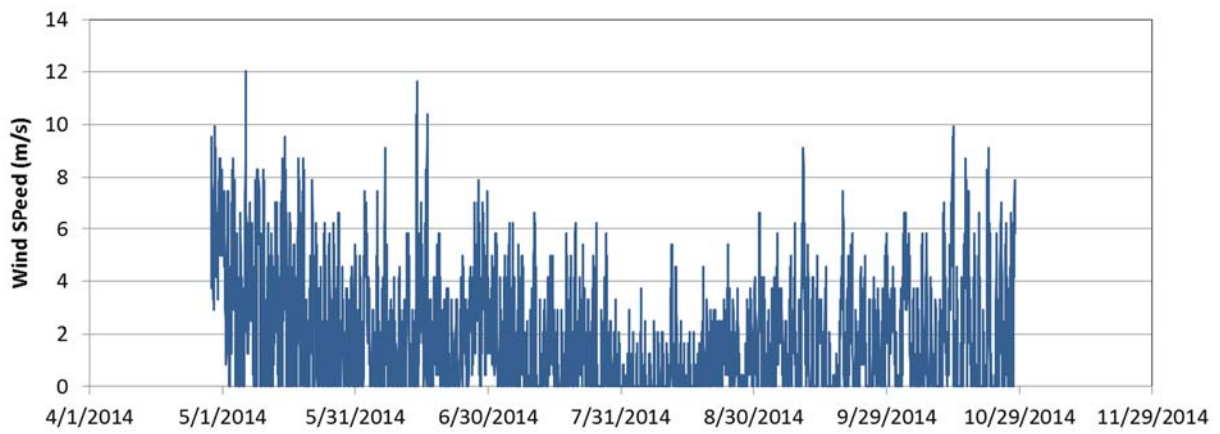
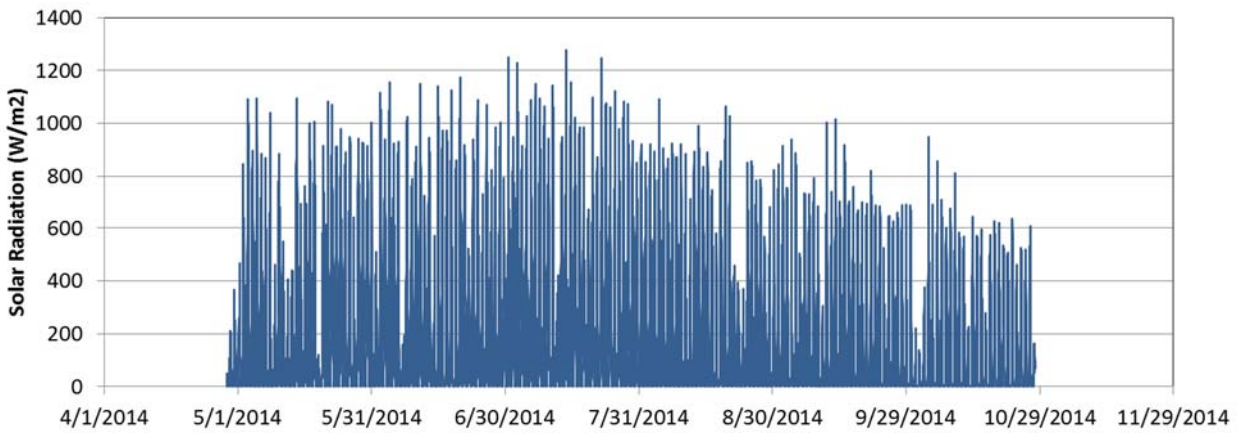
2012 Climate Data, continued



2014 Climate Data



2012 Climate Data, continued



Appendix II. PC-SWMM stormwater input points mapped to the CEQUAL model

PC-SWMM Junction	UTM_X	UTM_Y	CEQUAL Node	DESCRIPTION
CBC-14	493121.1	221605.1	13	Downstream of TH96
CBC_DN_1025	496908.1	219031.8	74	Upstream of McKusick Road
CBC_DN_1022	497404.6	218451.0	82	Upstream of Neal Avenue
CBC-15a	498028.4	218347.9	89	Diversion
CBC-16b	498031.9	218276.5	90	Downstream of BC Trail
CBC_DN_1018	499465.7	218769.5	103	BC at Oak Glen GC
CBC-16e	499827.9	218815.3	107	BC at Oak Glen GC
LBC-5a	499867.5	220017.5	117	BC at Oak Glen GC
LBC-new2	501708.4	220348.8	136	BC Gorge
LBC-3	503919.9	220258.2	154	BC Gorge
LBC_DN_1005	505726.8	220448.2	170	BC Gorge

